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ADVISORY GROUP FOR AEROSPACE RESEARCH & DEVELOPMENT

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AGARD Flight Test Techniques Series Volume 5 on Store Separation Flight Testing

by

R.J.Arnold and C.S.Epstein

Edited by

R.K.Bogue

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STORE SEPARATION FLIGHT TESTING

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A Volume of the

AGARD FLIGHT TEST TECHNIQUES SERIES

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PREFACE

Since its founding in 1952, the Advisory Group for Aerospace Research and Development has published, through the Flight Mechanics Panel, a number of standard texts in the field of flight testing. The original Flight Test Manual was published in the years 1954 to 1956. The Manual was divided into four volumes: I. Performance, II. Stability and Control, III. Instrumentation Catalog, and IV. Instrumentation Systems.

As a result of developments in the field of flight test instrumentation, the Flight Test Instrumentation Group of the Flight Mechanics Panel was established in 1968 to update Volumes III and IV of the Flight Test Manual by the publication of the Flight Test Instrumentation Series, AGARDograph 160. In its published volumes AGARDograph 160 has covered recent developments in flight test instrumentation.

In 1978, the Flight Mechanics panel decided that further specialist monographs should be published covering aspects of Volume I and II of the original Flight Test Manual, including the flight testing of aircraft systems. In March 1981, the Flight Test Techniques Group was established to carry out this task. The monographs of this Serics (with the exception of AG 237 which was separately numbered) are being published as individually numbered volumes of AGARDograph 300. At the end of each volume of AGARDograph 300 two general Annexes are printed; Annex 1 provides a list of the volumes published in the Flight Test Instrumentation Series and in the Flight Test Techniques Series. Annex 2 contains a list of handbooks that are available on a variety of flight test subjects, not necessarily related to the contents of the volume concerned.

Special thanks and appreciation are extended to Mr F.N.Stoliker (US), who chaired the Group for two years from its inception in 1981, established the ground rules for the operation of the Group and marked the outlines for future publications.

In the preparation of the present volume the members of the Flight Test Techniques Group listed below have taken an active part. AGARD has been most fortunate in finding these competent people willing to contribute their knowledge and time in the preparation of this volume.

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RESUME

Ce volume paraissant dans la série Technique des Essais en Vol d'AGARD traite des essais de séparation d. ·es en fonction de l'ensemble dcs systèmes. Tous les aspects des essais, portant sur la période d'identification d'un bc particulier avion/charge sont décrits, étape par étape, conduisant à l'établissement d'une enveloppe d'emploi satis L'accent a été mis principalement sur le planning et l'exécution de la phase d'essais en vol du programme autorisé (de charges, y compris la définition d'une structure de base, et sur l'ensemble des procédures qui augmentent la sécu l'exécution efficace d'un tel programme.

Cette AGARDographie a été publié à la demande du Panel de la Mécanique du Vol de l'AGARD.

STORE SEPARATION FLIGHT TESTING

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1.0 SUMMARY

The separation of stores from aircraft is an old story - the accurate prediction of the store trajectory during separation from the aircraft is not. Prior to the 1960's, there were virtually no widely used or generally accepted methods available for pre-flight prediction of store separation trajectories other than wind tunnel testing techniques. With the advent of modern high-speed attack or fighter-bomber jet powered aircraft, the requirement to carry more and more stores, and to release them at higher and higher speeds emerged. High transonic, and even supersonic, release speeds became commonplace requirements. It became obvious that the classic old wind tunnel store separation techniques were no longer adequate. With the aerodynamic sophistication of new aircraft came a better understanding of transonic aerodynamics and a more thorough knowledge of the complex aerodynamic flowfield surrounding the aircraft. Not until the virtual explosion in high-speed digital computers, however, did advances in both wind tunnel and theoretical prediction of store separation trajectories occur. Today, there are literally dozens of wind tunnel, wind tunnel/analyses, and purely theoretical analytic methods of store prediction available to the separation analyst or engineeer. The literature abounds in technical reports and descriptions of these techniques. The problem is which of the new techniques applies best to the problem at hand. Each method has its advantages and disadvantages, when it can be applied and when it can not, and its accuracies and inaccuracies. In nine out of ten cases, the engineer finds that several of the techniques could be used, and that the best method for the task must be selected using non-engineering criteria - usually cost or time available. For this reason, various companies, organizations, and government agencies have picked a set of methods which generally serve their needs. There is no set technique, or group of techniques, that one could describe as preferable for all users.

The purpose of this report, then, is to document the various aspects of a store separation program - what they are and what methods are being used by the US and other NATO nations to address these phases. The report is primarily intended for use by managers and new engineers to the field, both in government and industry, who are responsible for the planning or execution of store separation programs. For this reason, this report provides the reader with an overview of store separation prediction, testing, and analysis techniques currently in use in the US and other NATO nations. It also provides a ready reference listing for the reader's further investigation, if desired, to learn more about the advantages and disadvantages, as well as the applicability, of each technique. It is intended to assist the reader in determining the best technique to be used on a particular problem, given a specific set of circumstances.

The authors have many years of experience and are thoroughly familiar with the store separation techniques in use in US government agencies and industry. Canada and several European countries were visited to determine how the problem was being handled there, why specific techniques were being used, how effective were these techniques, and why a specific technique was chosen in the first place. A further objective was to determine how well the other nations understood some of the basic store separation prediction and testing techniques, whether they had made any changes or improvements to these basic techniques and, if so, why. From this, this report has been prepared which hopefully provides the reader with an understanding of store separation problems, the techniques used to treat these problems, and the set of circumstances (such as time or funding constraints) that govern the selection of the techniques used. Throughout the report, the authors have made maximum use of experience by the inclusion of examples from specific tests.

2.0 INTRODUCTION

2.1 Historical Perspective

The separation of stores from aircraft goes back to the early days of this century - prior to World War I. Even up to the post World War II period, the only reasons stores were dropped during testing were to test the store itself or to obtain sight settings needed for accurate stoes delivery. The rapid development of the jet engine following world War II, however, allowed fighter type aircraft to carry large payloads of stores externally on their wings and/or fuselage. Store delivery speeds begin to approach Mach One. Suddenly, it was no longer possible to merely drop stores and obtain ballistic data. The very art of separating the store from the aircraft became a problem in itself; one worthy of careful preflight consideration and in-flight caution.

The compatibility of stores with aircraft requires several types of engineering analyses and flight testing; structural, flutter, performance, stability and control, ballistics, electromagnetic compatibility, and separation are primary disciplines. By far the most visible of these - and one of the most critical from a flight safety standpoint - is store separation. It may also be the least understood of all the disciplines. Virtually every university that offers a course in aeronautical engineering covers thoroughly the disciplines of aerodynamics, loads, stress analysis, flutter, performance and stability and control, and so forth. To the authors' knowledge, none offer course in store separation at the undergraduate level. A few, however, do offer courses at an advanced de level. Because of the above, the Air Force's Office of Aircraft Compatibility (OAC) at Eglin Air Force Base, Florida has developed its own training program. The syllabus outline is contained in Table I. It is recommended that every organization performing store separation work have a formal training program.

Store separation is of major concern to all Air Forces today, and is a major sub-specia of engineering. Despite this, engineers and scientists working on problems of store separation ha largely developed their own tools (both academic and empirical) and have achieved success through experience on the job. It is in the hope of assisting the managers and engineers in rapidly acqui this on the job experience that this report is written. The report will not provide the reader with the proper way of performing store separation analyses of flight tests. Rather, it will attempt to explain the problems and discuss the ways in which the USAF, and particularly the way the OAC has dealt with the problems over the years. In addition, and perhaps more importantly, the reasons why particular methods are good in a certain particular set of circumstances will be discussed. The overall intent is to provide some "lessons learned" and an outline of successfully used methods and guidelines on how to choose the method that best meets the user's meeds.

2.2 Safety of Flight Hazards

As mentioned previously, prior to the 1960s, stores were placed on aircraft with little or no thought of eventual store separation. Store bays of heavy bombers were designed to pack as many stores inside as possible. When released, the stores were expected to fall out properly. External carriage of stores on fighter-type aircraft was generally limited to two or four stores per aircraft - each carried on its own separate pylon (single carriage). As aerodynamic design and available jet engine power allowed larger and faster aircraft, store separation became more and more of a problem, particularly as release speeds became transonic (above 0.8 Mach). The old standby of gravity release of stores became unacceptable and the first store Ejector Release Units (ERUs) were incorporated into aircraft. Ejecting a store from an aircraft with pneumatic or gas power, rather than merely releasing it, solved the store separation problem for a short time. As engine power available grew rapidly, so did the size and payload of fighter aircraft. Again, however, stores were carried largely on the basis of how many could be physically installed. With the larger number of stores came more complex arrangements for carrying the stores (such as on multiple, triple, or twin ejector racks). Virtually every fighter aircraft in use today by the NATO Air Forces uses forced ejection of stores and some sort of multiple ejector rack.

When the complex schemes for the carriage of large numbers of stores externally on fighter aircraft are mixed with the equally complex aerodynamic flowfield surrounding modern swept wing fighters, serious problems in store separation can occur. But it should be stressed that store separation problems may occur throughout the aircraft's flight envelope - not just at the high speed/high Mach points. The aerodynamic flowfield around the aircraft dictates when these problems occur. They may occur at low speed/high angle of attack, high speed/low angle of attack, high dive angle/low "g", or where sharp changes in the flowfield occur rapidly (such as when a shock wave forms or when critical Mach for the particular wing airfoil shape is reached). Generally, store separation problems fall into three distinct areas: store-to-pylon/rack collisions, store-to-aircraft collisions, and store-to-store collisions.

2.2.1 Store-to-Pylon/Rack Collisions:

When a store is ejected or released, the most likely problem that could occur is that the store might pitch, yaw, or roll more rapidly than it displaces away from the aircraft. If this occurs, the store will usually collide with the closest part of the adjacent structure - the pylon or rack from which it was released. Store-to-pylon/rack collisions usually occur within 200 milliseconds from release and may result in some bending or breakage of portions of the store or pylon rack. Aside from the fact that any such collision is undesirable and unacceptable operationally, store-to-pylon/rack collisions are not usually in and of themselves dangerous or serious. If, however, a store suffers breakage or bending of a fin, or becomes unpredictable, more serious collisions with the aircraft or with other stores may occur. The most common scenario for this type of collision is where the store pitches violently nose-down immediately after release causing the stores's tail to rise upward, striking the pylon or rack. Generally, after sustaining some bending of the store's tail, the store will fall away and assume a violently erratic ballistic trajectory. Although the store will not further endanger the aircraft, it may, due to its high drag erratic movements, impact the ground as much as several thousand feet short of the intended target. This could prove disastrous if the aircraft were operating in close support of friendly ground troops. The over-rotation, or violent pitch-down, of the store generally occurs when there is a large nose-down moment on the store while it is in the carriage position. When the store is released, this moment causes an immediate nose-down pitch. This situation could be caused by a large upward flow on the tail of the store, causing nose-down pitch at separation, but this is not as common in our experience. Usually, it is either a pure nose-down load on the store nose or a combination of nose-down load on the nose and tail-up load on the tail. Rarely is it a result of a pure tail-up load. The phenonomen causing this situation may appear rapidly and with little warning, or it may just get worse as flight limits are varied. For example, violent nose-down pitch of stores released from the bottom position of a Triple Ejector Rack (TER) on most USAF fighter aircraft occurs at speeds around 450 KCAS and worsens predictably as airspeeds are further increased. At 550 KCAS, this nose-down store pitch may reach ninety degrees (particularly for large diameter blunt nose stores such as the CBU-24/58 series) and this almost always causes store-to-rack collisions. Whereas the TER problem occurs at high speeds, pitch-down may also occur at low speeds. When aircraft employ thick wings with high camber airfoil sections, flow separation may occur at relatively low airspeeds, and this separation will occur rapidly and with little warning. On the B-57 and A-10 aircraft, uneventful store separation can be made at speeds up to 325 KCAS. However, if airspeed is increased to 350 KCAS, flow separation occurs (because Mach critical has been reached for the particular airfoil section) and some stores will pitch violently nose-down when released. Detailed testing has been performed on the A-10 and this testing corroborates that onset of flow the separation described occur over a 10-20 KCAS speed range.

2.2.2 Store-to-Aircraft Collisions

Although store-to-rack/pylon collisions are obviously also collisions with the aircraft, they have been broken out separately to distinguish them from those in this section. Store-to-aircraft collisions, as used here, involve collisions after release of the store with other parts of the aircraft such as wings, fuselage, or empennage. Collisions of this type are by far the most serious from an aircraft safety standpoint. Since they occur at some time and distance from the initial point of release, the stores are moving rapidly, and their mass, impacting the aircraft at high energy and high speeds, can cause serious aircraft damage.

Ideally, when a store is separated it should pass through the aircraft's aerodynamic flowfield into undisturbed air as quickly as possible. If this does not occur, and the store remains in the aircraft flowfield, the flowfield forces begin to dominate and to determine the store's movements. When this happens, a store/aircraft collision is highly likely. There are several reasons for a store remaining in the aircraft flowfield too long. The primary reason is not enough store ejection force. This may occur because the ejector rack cannot produce enough force, or it may occur because the flexibility of the rack or aircraft supporting structure reduces the effective force pushing the store away. In effect, the aircraft pylon or wing is pushed upward while the store is being pushed downward, resulting in less separation between the aircraft and the store. Effective ejection force may also be reduced by releasing the store at low "g" levels. Since gravity usually assists in store separation, lowering the gravity force lowers the total, or effective, separation force.

When a store is released at high speeds and remains in the aircraft flowfield too long, enormous forces may be generated which can drastically affect the store's separation trajectory. Viewers of store separation films are often amazed to see a 500 or 1000 pound store start its separation downwards only to later rise back up into or even over the releasing aircraft. Figure 1 shows an example of the above. In this sequence, a BLU-1 firebomb is ejected from an F-105. It starts downward, pitches nose-up due to flowfield effects, and is then swept upward by the flowfield, impacting the aircraft's horizontal tail. Figure 2 shows an identical occurrence on an A-7 aircraft with a MK-77 firebomb. Figure 3 shows a sequence which ends with a spectacular collision between an empty fuel tank and pylon on an FB-111. What starts as a good separation soon becomes a serious collision as the fuel tank rotates ninety degrees, picks up lift from the pylon (now acting as a wing), and rises to collide with the aircraft's aft fuselage. Figure 4 shows the gravity release of an empty fuel tank from an A-37 aircraft. Although this release was made at less than 250 KCAS, the empty fuel tank is large and light (low density). The aircraft flowfield immediately causes a nose-up pitch of the fuel tank, and it remains in contact with the aircraft wing until it has scraped the wing from the leading to the trailing edge. A final sequence, Figure 5, shows store-to-aircraft collisions which occurred when MK-20 Rockeye cluster bombs were separated from an A-7 aircraft. The MK-20, being marginally stable until its fins open, remained in the flowfield because of a low effective ejector force and because its fins did not open properly. This allowed the flowfield aerodynamic forces to sweep the store inwards towards the aircraft. This condition was initially aggravated by the stores being released in a high dive angle (sixty degrees) at low "g", further reducing the effective ejection force.

2.2.3 Store-to-Store Collisions

When released, stores may collide with other stores still attached to the aircraft, or they may collide with others that may have also been released. When the collision is with other stores not yet released, the comments of the previous paragraph apply. However, when the collision is between stores which have already been released, several things may occur: one or both could explode, one or both could sustain damage, or one or both could be knocked into an unstable trajectory thereby affecting accuracy. Of the three, the least likely to occur is explosion, particularly if the collision is immediately after release. Generally, the store fuze will not have had time to arm (normal setting is several seconds after release) and a side-to-side collision (the most likely) will not be of sufficient force to cause explosion or fuze function. While not desirable, side-to-side collision of stores immediately, or shortly after, release is sometimes inevitable and must be expected, particularly when large numbers of stores are released simultaneously or in a short interval ripple release mode. Photographs of the release of eighty-four MK-82 500 pound stores from the bomb bay of the B-52, for example, show many low energy, side-to-side collisions of stores, but they do not adversely affect safety or the ground pattern. If the collisions occur appreciably after release, they may be of the high energy type, again because the time period has allowed their speed relative to one another to be high. If this type of high energy collision occurs, it will generally result in damage to one or both stores. What happens thereafter is a function of what damage occurs. Store-to-store collisions are not usually a safety hazard to the releasing aircraft, but as described in the previous section, they can cause serious safety hazards to friendly troops on the ground by affecting the stores's ballistic trajectory.

One type of store-to-store collision can be a hazard, but usually occurs well away from the releasing aircraft. If a number of stores are released simultaneously, or at very short intervals, stores may "draft" on one another. Specifically, if two stores are in ballistic flight, one directly behind the other, the rear one will be in the wake of the lead store and the drag of the rear store will be lessened. This can allow the rear store to speed up and collide with the lead store. If this occurs, an explosion is highly likely since the fuze on both stores will usually have had time to arm. One remedy to this "drafting" is to increase the interval between stores, particularly for stores released from tandem carriage positions. "Drafting" has proven to be quite predictable for the same typ. of store released from specific carriage racks. For example, Figure 6 shows the time it takes for MK : SNAKEYE bombs to collide (nose-to-tail) with one another when released from tandem stations on a iple Ejector Rack (MER-10) at 450 KCAS. This plot was formulated based on literally hundreds of releases. Note that for a simultaneous release (zero release interval) the bombs collide almost immediately. If the bomb fuzes were set to arm immediately after release the bombs would explode. At the other end of the scale, note that with an interval of 240 milliseconds, the bombs never collide. The reader may believe at this point that the solution to the problem would be simply to limit the minimum release interval to 240 miliseconds. Unfortunately, in most instances users desire much lower intervals. Another way around the problem, if the aircraft has several store carriage pylons, is to sequence stores release from pylon-to-pylon thereby increasing the interval between tandem stores off the same rack. Store-to-store collisions can under certain circumstances be accepted so long as they occur outside the aircraft's fragmentation envelope. Incidentaly, as airspeed is increased, the time it takes for stores to collide decreases. That is, at 500 KCAS, 300 miliseconds may be required to preclude drafting instead of 240 milliseconds at 450 KCAS. In addition, the time it takes for stores to collide is a function of the stores themselves. For example, stores released in a high drag mode such as the MK-82 SNAKEYE will clearly require higher intervals to preclude drafting than a MK-82 SNAKEYE released in the low drag mode.

To conclude this section, Figure 7 shows an example of multiple store-to-store collisions when BLU-80 stores were released from an A-4 aircraft. Note that one store contacted the centerline mounted fuel tank causing it to break off the aircraft. The tank then contacted another BLU-80 released from the other side of the aircraft breaking off the store fin. Obviously, not a satisfactory situation.

2.3 Historically Difficult Store Separation

Over the last two decades, many different kinds of stores have been separated from many different kinds of aircraft. Although each aircraft/store combination provides its own problems there have been several types of stores (and release conditions) that have historically been problems no matter what aircraft was used. These are:

- Low density unstable stores
- Stores with folding fins
- Liquid filled stores
- Jettison of fuel tanks, pylons, and racks
- Ripple release of stores

Low density unstable stores, that is, those whose static margin is either negative or near zero and whose aerodynamic loads are large in comparison to their weight, have always been a problem no matter what the release airspeed. Examples of this type store are empty rocket pods (such as a LAU-3) and training dispensers (such as a SUU-20). Being unstable, even a small aerodynamic disturbance will cause large deviations in store separation trajectories. Also, being light in weight, the store may be moved with small disturbances. The result is, usually, extremely large angular and displacement departures during separation, and a highly unpredictable separation trajectory. Most of the spectacular store-to-aircraft collisions seen in films have been of this type. Also, because of the extremely large angular movement of the stores - sometimes resulting in tumbling - many store separation prediction methods will not accurately simulate the store's trajectory so flight testing should proceed very carefully.

Almost as dangerous as low density unstable stores are those which have fins that open after release. Such stores (like the MK-20 Rockeye and many of the guided stores series like the GBU-10 and GBU-12 are almost always high density (aerodynamic loads are not as high as inertial loads) but, because of their folding fins, they are also almost always unstable, or nearly so until their fins open. Therefore, immediately after release these stores sometimes start to move with large angular or linear motions. Even when the fins open, the additional stability often cannot correct these motions quickly enough to prevent the store from moving and striking the aircraft or other stores. Such problems are greatly aggravated by slow opening fins. Consider the following examples:

- The MK-20 store, used by several NATO Air Forces has four fins which are supposed to open independently (each fin has its own spring) in less than fifty milliseconds after release. However, because of different aerodynamic forces acting on each fin and because some springs are more powerful than others, the fins almost never open simultaneously. As a result, this store is one of today's most unpredictable and dangerous stores to separate from any aircraft. Recall Figure 5 which shows MK-20's released from an A-7. On this mission, MK-20's collided with the aft fuselage of the A-7 causing substantial damage. MK-20 separation trajectories did not match predictions because the fins did not open equally as can be seen in the second frame. Unequal fin opening was directly responsible for the erratic and unacceptable separation shown in this figure. It may be noted that at the time of this writing, the USAF was considering a modification to the MK-20 which consists, among other things, of stronger springs. While these springs are expected to speed up fin opening there is still no guarantee that the fins will open simultaneously since the fins still will not be interconnected.

- The GBU-10C/B and GBU-12B/B consist of 2000 and 500 pound bomb bodies respectively with nose and tail assemblies which convert the general purpose bombs into laser guided bombs. Like the MK-20, the fins are designed to open very rapidly, but in flight they do not. However, on the positive side, the fins are interconnected with one another so they at least open simultaneously. The fins on the GBU-10C/B are particularly slow in opening. In fact, they open so slowly that store separation analyses and flight testing has been structured assuming that the fins do not open at all in the near vicinity of the aircraft. This approach was used in certifying the GBU-10C/B on the A-10, A-7, and several other aircraft.

In short, stores with opening fins should be tested very carefully if the fins do not open simultaneously or if they do not open rapidly. Ideally, stores should be designed with a mechanism to insure rapid opening of interconnected fins. Explosive cartridges used to power the fin opening mechanism is an example of one successful approach.

Liquid filled stores (such as fuel tanks and firebombs) pose a unique store separation problem. Sloshing of the liquid fill can radically change the inertial characteristics of the store and cause an extremely unpredictable, erratic separation trajectory. Sometimes these changes in inertial properties can act as a damper on the aerodynamically produced loads and result in a very flat, uneventful separation. At other times they will add to the aerodynamic loads and produce drastic store displacements and angular rotations. There are no easy solutions to the problems associated with this type store. Ideally, the store should be designed with internal baffling to prevent all the liquid from running to the store's nose if the aircraft were to approach the target in a dive angle. At best, liquid filled stores are unpredictable and erratic and, therefore, dangerous and should be tested with extreme caution. One word about testing liquid simulant filled stores. The authors have found that it is virtually impossible to simulate most liquid fills. For example, for years the USAF filled firebombs with Vermiculite (a low density water absorbing material) and water to the proper weight and center of gravity as a simulant for napalm. The Vermiculite absorbed the water and prevented slosh. Others in the United States used a dessicant (such as floor sweep) and water in a similar manner. It was later discovered that firebombs released with these simulants did not follow the same store separation trajectory as those filled with real napalm. This was proved during A-7 testing when live firebombs (real napalm with inert fuzes) were released from one wing and simulant filled firebombs were released from the other wing in the pairs mode (that is, one from each wing at the same time). Firebombs filled with simulant separated with slow nose-down pitching motions whereas the live firebombs separated with minimal pitching motions but large yawing motions. As a result of this experience, and others, the USAF now only allows real napalm in all separation testing of firebombs.

Using real napalm fill and inert bomb fuzes does not pose a flight safety problem. Even if store collisions occur, no ignition of the napalm will occur. In this regard, it may be noted that for a recent test of a firebomb on a aircraft, live napalm was used. The stores had to be used within a specified period of time after they were filled because the napalm mixture decomposes with time and that could change its slosh characteristics. In addition, the largest source of error comes from the machine that mixes the napalm. When the machine is clean, the first firebombs filled will be of proper weight and center of gravity. Later in the day, when the machine becomes partially clogged, firebombs will be filled with a completely different density mixture. As much as 90 pounds difference has been observed in one day for a 750 pound store. For liquid filled stores (other than napalm), it is absolutely essential that any liquid used to simulate the liquid fill (when the real liquid just cannot be used for whatever reason) not only simulate the weight and center of gravity, but also the density and slosh characteristics of the real fill. The bottom line is that great caution must be used in filling and separating liquid filled stores.

Jettison of fuel tanks, pylons, and racks combine all the above problems. Fuel tanks, pylons, and racks all are unstable aerodynamically, and they also are usually of low density. Fuel tanks, even if supposedly empty, usually contain some residual liquid. Pylons and racks are of such irregular aerodynamic shapes that their separation trajectory is almost impossible to predict. At best, they may be simulated in a wind tunnel. The word jettison is usually defined as getting rid of something no longer wanted. So it is here. Jettison of fuel tanks usually means an empty or partially full tank. Jettison of pylons and racks is usually done in an emergency condition and may mean with or without some or all of the stores still attached. The combinations one would have to analyze, for example, on an A-7 aircraft with six pylons (or the A-10 with eleven pylons), many of which are capable of carrying a multiple ejector rack, are enormous. Since jettison is used in an emergency condition, and since such testing flight can be very dangerous, fuel tank, pylon, or rack jettison is normally studied extensively in a wind tunnel (and most frequently using the drop model technique). Even then, remembering the F-111/fuel tank sequence in Figure 3, dangerous store separation can still occur.

Ripple release of stores in very small intervals can also pose another very dangerous separation problem. When store separation is studied in a wind tunnel, the aircraft model may have many stores loaded, but only one is released at a time (except when the drop model technique is used). The airflow around, say, twelve stores released in a ripple sequence at a small interval, will be considerably different because the individual stores disturb the airflow of the other stores. Thus, wind tunnel and computer predictive methods are marginally effective at best. Ripple release, however, is a very common operational requirement and must be cleared. Such multiple releases are normally made in flight using "brute force" methods. That is, a multiple or ripple release is made at a safe airspeed in level flight using a high release interval (intervals in excess of 200 milliseconds). If stores separate without store-to-store collisions, the interval is lowered, and the flight conditions are increased until flight limit goals are achieved or store-to-store collisions occur (presuming these collisions occur well below the aircraft so that they do not pose a safety of flight hazards). Another reason why analytical and wind tunnel methods are not always successful in predicting actual stores separation is rack flexibil cy. The ejection force imparted to stores carried on the various stations of a MER are all different due to rack flexibility. As stated earlier, there is no substitute for flight testing when it comes to establishing safe separation envelopes for stores released in the ripple mode.

2.4 Accuracy Consideration:

In pursuit of safe store separation, the point must not be overlooked that stores are being separated for the purpose of hitting a target. If the store clears the aircraft safely but then, due to collisions, unstable motion, or other problems, does not follow its expected ballistic trajectory, that is often just as unacceptable as a store-to-aircraft collision. There are always certain factors present that can cause inaccuracies in stores delivery; wind conditions, optical sight error, pilot error, store manufacturing tolerances, and so forth. Some of these factors may be compensated for; however, there are other factors which cannot. If the store is marginally stable or unstable, its trajectory is erratic and not repeatable. Likewise, if a guided weapon is released and experiences some severe angular pertubations, the store control system may not be able to return the store to a trajectory that will allow it to hit the target. One can imagine the pilot's reaction when the AIM-7 missile depicted in Figure 8 was launched from the F-15. This missile certainly did not hit its intended target. The problem was caused by the aircraft flowfield generating more nose-up pitch than the missile's control system could correct for.

3.0 REQUIREMENTS FOR A STORE SEPARATION PROGRAM

3.1 Determining Operational Requirements for Certification

In the United States, operational users (such as the Tactical Air Forces) generate certification requirements. Requirements are transmitted to higher headquarters under the auspices Certification Request (CR). If the CR is approved (validated), then the cogizant Aircraft Program Office (APO) on which the store is to be certified is responsible for arranging and managing analyse and testing necessary to establish aircraft carriage and store employment envelopes. In addition, t APO is responsible for insuring applicable Technical Orders (T.O.s) are amended so the store may be carried and employed operationally. Typical T.O.s include the aircraft -1 series which contains aircraft/store carriage and employment limits and other operational restrictions, the aircraft -33 series which contains aircraft/store loading and functional procedures, and aircraft -34 series wh contains store delivery and ballistic tables and procedures.

Because of constantly changing user requirements and the large number of CRs that are generated, the USAF instituted a management program to process and approve/disapprove CRs from us and to track the status of validated CRs. This program is called "SEEK EAGLE" and has worked extraordinarily well over the last eighteen years its has been in use. Therefore, additional disc on the SEEK EAGLE program and how it fits into establishing a store separation program is in order Although the SEEK EAGLE program was established for the USAF, the authors feel that the reader wil gain from the knowledge of how and why this program was begun. Authority for the SEEK EAGLE progra rests with Program Management Directive (PMD), Reference (1), established by Headquarters (HQ) USAF This PMD defines the specific procedures for submitting CRs to HQ USAF and cognizant APO. For eac the user must provide the following information:

Aircraft/Store Configuration

The user must specify each type of store desired to be carried on each aircraft pylon s and whether the store is to be carried on parent pylon or multiple carriage racks. There is a huge number of possible aircraft/store configurations and the configuration actually required drives the scope, cost, and schedule of compatibility analyses and testing. For example, it would be unsatisfactory for the user to state a requirement to carry MK-82 bombs in combination with CBU-58 dispensers on the A-7. The A-7 has three pylons on each side of the wing and it should be obvious carriage of a pylon mounted MK-82 on the center pylon and a fuel tank on the inboard pylon (Figure would require far less analyses and tests than if these same stores were mounted on multiple carriag racks as shown in Figure 10.

Specific Store Type Required

Because there are so many versions of some stores, it is mandatory that the user define the specific store type required. For example, it is not satisfactory to just specify a requirement to certify the MK-82 because there are MK-82 LOGP (low drag general purpose), MK-82 SNAKEYE (retarded fin assembly), MK-82 Air Inflatable Retarder (airbag retardation device), and even other versions with an array of fuzing options. Another example is the GBU-10. The GBU-10 consists of a MK-84 (2000 pound) general purpose bomb body with nose and tail assemblies which convert a "dumb" bomb into a "smart" laser guided bomb. However, there are many nose and tail assemblies each of which give the GBU-10 a different designation. For example, the GBU-10A/B has a fixed tail fin assembly whereas the GBU-10C/B has a tail fin assembly which opens immediately upon release from the aircraft (see Figure 11). Clearly, the user must specify in detail which version, or if all versions, are required for certification.

Carriage and Employment Limits

The user must specify the limits required. Typically, users ask for more than they need. For example, if the aircraft's maximum carriage speed is 600 knots and a carriage speed of 500 knots is actually required, 600 knots is often requested. Users have told the authors that they fear that if the true carriage requirement were specified, the technical community might only perform analyses and testing to even a lesser speed to reduce time, cost, complexity and so forth. This is, of course, not true. If any event, users are required to specify required carriage speeds, load factors, maneuver limits, employment speed, dive angles, release intervals, and other applicable information.

Justification

The user must explain why the CR is required. Usually, the user explains that the mission cannot be accomplished, or will be adversely affected, unless the new store configuration is certified, or if present limits for a certified store configuration are not expanded. Certainly the USAF will not approve a CR unless a strong justification is provided and it must be defended by the user if challenged.

Priority

The user must specify (in terms of the USAF Precedence Rating System) the priority attached to the CR. This forces the user to let HQ USAF know how badly the CR is really needed. In effect, if the user has 100 outstanding CRs and APO funds are limited, and if the new CR is assigned a priority of 101, the new CR would probably never get acted upon even if it were to be validated by HQ USAF. If on the other hand the new CR was assigned a high priority, a lower priority CR would get postponed, perhaps indefinitely. Obviously, the priority of the CR will ultimately impact scheduling of analyses and tests performed by the engineering organization, particularly if the engineering organization is already working on several other CRs.

Required Certification Date

The user must specify when the CR is required in the field. Clearly this date ties in closely with priority. A long lead time enables the APO to smoothly integrate new CRs into ongoing workload activities. Short lead times are highly disruptive to ongoing activities.

It is clear that with the above information, HQ USAF has the necessary information to assess the user's CR in terms of overall USAF requirements. In addition, the APO has the necessary information with which to formulate a cost estimate for the engineering organization to perform analyses and tests. HQ USAF makes the final decision as to whether or not the CR should be validated based on meshing overall operational requirements with cost considerations. If the CR is validated, the SEEK EAGLE PMD is amended, and once amended, the cognizant APO is responsible for effecting certification. After the store has been certified (all T.D.s amended) the APO advises HQ USAF who then deletes the CR from the PMD, thereby completing the SEEK EAGLE process.

It should be noted that the above management procedure is used for CRs which involve inventory stores (such as a MK-82 LDGP bomb) on inventory aircraft (such as an A-7D). The management process is essentially the same for developmental stores. Validated CRs for developmental stores are placed in a separate annex of the PMD. So long as the store remains in this annex the APO is not required to take certification action. Instead, the APO is required to monitor store development (such as ongoing analyses and tests), and take necessary actions to plan for certification (such as the need to fund for aircraft software modifications to function and employ the store). Once, and if, a production decision is made for the store, it is removed from this annex and placed in the inventory store annex. At this point, the APO must take action to effect certification. There are many cases where developmental stores do notgo into oroduction. In these cases, the store is deleted from the PMD. Dne last point on the SEEK EAGLE process. The SEEK EAGLE PMD is an unfunded document. Thus, if a high cost, short notice, CR is validated by HQ USAF and the APO does not have the funds required to effect certification, no action is taken until the APO requests and receives supplemental funding. Usually, some funds are available to handle short notice CRs but these are reserved for high priority efforts.

3.2 USAF In-House Compatibility Analysis and Test Capability

Once a CR has been validated, analyses and testing required to establish captive carriage and employment envelopes may begin. But who is to perform this work? In the United States the question narrows down to industry or the USAF.

In the mid 6D's, USAF engineering personnel were not oriented or trained to support aircraft/store compatibility efforts. During this period of time there was a tremendous quantity of CRs being requested and approved by HQ USAF. Most of these CRs were required yesterday. That is, there was an immediate operational requirement. Yet, because the USAF did not possess its own in-house capability, all analyses and tests required for certification were performed by industry (usually the prime aircraft manufacturer) under contract. Because of the long lead time required to award a contract, stores were frequently not certified in a timely manner which adversely impacted combat operations. Another problem was that as soon as the contract was awarded, user requirements frequently changed. This required a contract amendment which took more time and funds. Because of these problems, the USAF perceived that they could perform compatibility analyses and testing more cheaply and quickly with their own personnel. To quantify perceptions, the USAF commissioned several independent studies which corroborated that compatibility analyses and tests for follow-on certification efforts could be performed in-house more responsively and at less cost than by contracting with industry for such support. Reference (2) documents results of such a study. The term follow-on is of significance in the study findings. It was, and is, acknowledged that the prime aircraft manufacturer is best able to establish the aircraft's basic structural and aerodynamic limitations for carriage of baseline store configurations. Baseline configurations are those which drive and influence the design of the aircraft (such as pylon stations, hard points, electrical, mechanical, stores management, fire control and so forth). In addition, baseline configurations are those that are critical from the disciplines of flutter, loads, stability and control and store separation. Enough baseline configurations should be analyzed and tested to correlate with predictions. However, once the contractor has established and demonstrated the ability of the aircraft to carry and employ baseline store configurations (usually 2D or less configurations), studies were unanimous in their findings that follow-on work involving the addition of new stores and configurations to the aircraft should be performed in-house. A complete description of what constitutes follow-on and baseline certification programs is contained in Reference (3). As a result of the above study results, in the late 60's, the USAF formed at what was then the Armament Development and Test Center (currently called the Armament Division), Eglin Air Force Base, Florida, an organization dedicated to monitoring contractor baseline analyses and tests and performing follow-on analyses and tests. This organization has evolved over the years and is now called the Dffice for Aircraft Compatibility (OAC).

The first major application of in-house resources was in support of the A-7D SEEK EAGLE program. By the time the A-7D program started, the Navy had already certified an array of store configurations on their A-7A/B. These became baseline configurations for the USAF. Many store configurations were just what the USAF required. However, there was a large group of additional stores (involving over two hundred configurations) which the USAF required to be certified. Because the USAF was just building up its in-house capability, no attempt was made to perform analyses to establish captive carriage envelopes. All captive carriage envelopes were established by the prime aircraft contractor. However, the contractor reports which documented the basis for the captive carriage envelopes were delivered to the USAF. USAF engineers used the data in these reports as a basis for establishing an in-house captive carriage analysis capability. Incidentally, several government organizations in Europe acquired their in-house capabilities in just this same way. The number of different store types and the variety of configurations in the contractor's data base was extensive. This made it relatively easy to formulate programs to predict aircraft flutter, loads, and stability and control characteristics for follow-on store configurations which were not in the data base. By the time the A-7D SEEK EAGLE program was completed several years later, a complete in-house captive carriage capability had been established and validated. This put the USAF in a posture to establish carriage envelopes for additional follow-on store configurations without the need for contractor support. In fact, this capability has been used extensively in just this fashion over the last 15 years. While the

USAF did not initially undertake the job of establishing captive carriage envelopes, the USAF did ass the job of establishing store separation envelopes and performing all flight testing. This in itself was a departure from the past when the USAF had contracted for all separation analyses and flight testing using contractor aircraft, pilots, and other resources. The only contractor support for th separation program consisted of two engineers who were assigned to work with USAF engineers in the One engineer was an aerodynamicist who helped train USAF engineers in the planning and conduct of tunnel tests, analysis of test data, formulation of flight test plans, and techniques for performi succeeding misisons based on results of data from preceeding missions. Another engineer was an ar ...t specialist who helped train USAF engineers in the verification of proper store loading and riggin procedures and establishing the functional adequacy of the aircraft/store configuration from an electrical/avionics standpoint. The training provided during the A-7D program served as the foun n for establishing a USAF in-house store separation capability.

Approximately ten wind tunnel test entries were made at the Arnold Engineering Develop Center (AEDC) in support of the A-7D SEEK EAGLE program. Store separation trajectories were esta ed in the AEDC four foot transonic wind tunnel using a Captive Trajectory System (CTS). The CTS wil described in a subsequent section. It is appropriate to state at this time that the CTS was chose the A-7D program because it was, and is, the easiest method for obtaining complete trajectories f viewpoint of the USAF. All the USAF had to do, and this was important because of limited technic expertise in the field at the time, was to specify the aircraft/store configuration, store release conditions, ejection force, and other applicable information. The wind tunnel engineers and the CT the rest. During the course of CTS testing in support of the A-7D program it became apparent to USAF that other wind tunnel test methods, such as drop model and grid, both of which will be desc later, were more efficient for selected applications. In short, the A-7D program opened the USAF and offered convincing proof that it could perform compatibility analyses and tests in-house. Ove hundred captive compatibility and store separation missions were successfully flown leading to certification of a huge array of store types and configurations. The A-7D program also validated earlier mentioned commission's belief that the USAF could do follow-on compatibility work cheaper (in terms of direct cost expenditures and faster than by contracting for support. In this case, the USAF had tangible evidence because the value of the A-7D contract was reduced by over $13,000,000 (in 69 dollars) by eliminating contractor flight testing alone.

Because of the success of the A-7D program, in-house capabilities were soon expanded to cover the F-4 and A-10. For both of these aircraft, the USAF initially obtained captive carriage envelopes from the contractor. Contractor reports were used to establish a captive carriage analysis capability for new store configurations as was done for the A-7D. However, unlike the A-7D, all store separation analyses and tests were performed by the USAF without contractor support.

In 1975, bouyed by increased responsiveness to changing operational requirements and by cost savings, HQ USAF established what was called an Implementation Plan. This plan required the USAF to establish in-house compatibility analysis and test capabilities for practically all inventory aircraft to the point where most work could be performed by the USAF.

Table II shows current USAF in-house analysis and test capabilities in the major compatibility disciplines. A few notes are in order at this point. Note that for F-111 flutter, the USAF presently has only a partial capability. This is a result of a conscious decision to not establish a full capability. To have done so would have been a complex technical undertaking due to the aircraft's high speed capability, many wing sweep angles and other factors. But, there was a more basic underlying reason. In the late 70's, it was assumed that operational F-111 aircraft would be out of the inventory within ten years and that as a result, few additional stores would be required to be certified. Accordingly, it was rationalized that it would be more costly to develop and maintain an in-house capability than to contract with industry for occasional compatibility work as the need arose. The other compatibility disciplines were not nearly as complex to develop and maintain, nor as costly, so these were established as contingencies for future work. Basically, time has proven that this was a sound decision. There have been a number of additional stores certified on the F-111, but few stores have required contractor analyses. Most stores have been cleared by analogy to certified stores.

This is an ideal time to dwell on the subject of whether the USAF, or any other Air Force, should or should not establish an in-house compatibility capability. Each Air Force knows its own requirements and these requrements drive the management and technical strategy. From the point of view of the USAF, if there is only an occasional need to certify stores on a given aircraft, the cost to establish and maintain in-house capabilities is not worth the effort. This is why such aircraft as the A-37, F-105, and B-52 are not shown on Table II. In-house capabilities are only established and maintained for aircraft that have continuing, and/or projected, store certification requirements of a significant scope. For aircraft which have few certification requirements, it is more cost effective, but not necessarily more responsive, for the USAF to contract with industry for occasional analyses than to maintain dedicated personnel and technical programs in a ready posture to perform work that may never materialize.

Note in Table II that a complete in-house compatibility analysis capability exists for the F-16. Because of the F-16's very high maneuvering capability and speed envelope, and other technical reasons, it was a major undertaking to develop a complete in-house capability. But, as stated earlier, because this aircraft has a current backlog of store certification work and a large projected workload as new developmental stores enter the inventory and are requried to be certified, the investment was worth it. To put into perspective how large the F-16 program really is, it can be stated that more store configurations have been certified on this aircraft in the last several years than on all other USAF tactical aircraft combined. Incidentally, the USAF certification program includes the certification requirements of the European Participating Group (member nations which operate the F-16) whenever feasible. This saves time and money and maximizes utilization of test resources.

An F-16 instrumented for loads, flutter, and stability and control is maintained at Eglin Air Force Base to support store certification programs. The task of installing and calibrating required instrumentation was complex and costly. Figure 12 shows the general position and types of instrumentation added to the aircraft. Because the F-16 is sensitive to the addition of stores an instrumented aircraft is mandatory considering the limitations of current prediction techniques. For example, even though in-house flutter prediction programs are considered to be state-of-the-art, flutter speed predictions have sometimes been conservative and sometimes optimistic. That is, a high flutter speed is predicted when the actual flutter speed is lower and vice versa. Let the reader not take this section out of context and conclude that the F-16 is overly sensitive to stores carriage. This is not necessarily the case. Many configurations are benign in all compatibility disciplines and are cleared to aircraft limits. It is just that prediction techniques are not perfect, especially when applied to an aircraft like the F-16 which has a flexible structure. An instrumented aircraft is required if every last ounce of usable flight envelope is to be obtained for each store configuration. This is precisely the opportunity an instrumented aircraft provides. When Eglin's instrumented F-16 is flown, real time data is telemetered to a Central Control Facility. In this facility, engineers monitor actual results with predictions and provide the pilot with go no-go recommendations for the next test point. This allows flight test missions to be flown efficiently (build up points can be performed during the same mission) and safely (results analyzed on the ground before going to the next test point while the aircraft is still airborne). One last point regarding the F-16. Because F-16 SEEK EAGLE activity has been so high, and expected to remain so, every effort is being made to continually enhance in-house capabilities. For example, the original F-16A/B capability has already been upgraded to include the F-16C/D and further enhancements will be made as new versions of the F-16 become available. Thus, unlike with lesser used aircraft, a complete in-house analysis and test capability is warranted.

Referring to the B-1 in Table II, note that in-house capabilities have not been established in a number of compatibility disciplines. This is because it would be premature to do so at this time. As mentioned in the beginning of this section, the USAF only establishes capabilities to perform follow-on store certification work after the contractor has established aircraft characteristics/limitations for baseline store configurations. In this case, the contractor is still performing baseline work. But, the USAF is acquiring contractor reports and the strategy is the same. At the appropriate time, a complete in-house analysis and test capability will be established, if warranted, by assessing current and future certification needs and balancing these against cost and schedule considerations.

In summary, the USAF performs as much compatibility work in-house as it possibly can because it is more cost effective and responsive to do so in the majority of cases. Each Air Force must, however, assess its own requirements before establishing an in-house capability for one or more aircraft types. If the certification workload is low, and if there is no urgency to complete the work, then contracting with industry will usually be more cost effective. It takes a certain minimum number of personnel to maintain an in-house capability. If workload is too low, personnel will be under utilized. That is why in the OAC the manning authorization is optimized based on a historical and predicted number of personnel to satisfy workload requirements. If a surge in workload develops, industry is usually relied upon as they have a greater flexibility in the ability to hire additional personnel to support the work at hand. The creation of a technical organization to support work that never fully utilizes personnel is a terrible waste of valuable resources and should not be tolerated under any circumstance. Table III shows the major steps involved in the USAF SEEK EAGLE program.

3.3 Coordination with Operational Users

Once a CR has been validated and the APO requests support from the OAC to perform in-house analyses and testing, additional dialog takes place with the APO and the user. Requirements (such as configurations and flight limits goals) are reviewed one last time to make sure that there has been no miscommunication. Priorities for individual configurations are reviewed from the user's standpoint and the technical community's standpoint. This is of major importance. Users always prioritize configurations required based on operational needs. However, the technical community prefers to prioritize configurations on the basis of expediency. For example, for some configurations on some aircraft, it may be more cost effective and schedule efficient to analyze and test configurations involving the same store released from a given pylon with different adjacent store loadings. On another aircraft a different approach may accelerate and simplify analyses and tests. The point is, once the technical community develops a prioritized list from the standpoint of analyses, schedule, and cost efficiency, the list must be re-coordinated with the APO and the user. Usually, but not always, the user is quite agreeable if all configurations can be obtained in a shorter span of time (or the same time span) than in a specific order. On the other hand, it has been our experience that users do not generally agree to re-ordered configuration lists on the basis of cost savings alone.

Next, the impact of required flight limits on the time and cost to perform analyses and tests is revisited. As mentioned earlier, a cost estimate is prepared for each CR and, until recently, the cost estimate was for exactly what was requested. In other words, assume that the user requested a carriage speed of 600 KCAS for a certain store configuration on a certain aircraft. Further assume that the cost to establish the captive carriage envelope is $250,000. What the user and HQ USAF may not realize is that if the carriage envelope were reduced to 550 KCAS, the cost might be reduced to only $25,000. This is not a far fetched example. One of the benefits of having an in-house capability is that this sort of trade-off can be scoped and considered. Experienced USAF personnel can quickly and independently weigh and assess the cost benefits to be derived by adjusting flight limits. In the above scenario, if cost were significantly less for a small decrease in flight limits the user might be agreeable knowing that, in times of limited funds on the part of the APO, additional configurations might be certified with the cost savings that otherwise might not get certified for a long time.

The best SEEK EAGLE programs have a Master Configuration List (MCL) to document agreements made between the user, APO, and the organization performing the analyses and tests. This list can and should be continually updated as configurations are certified and as user requirements dictate changes. For many of the programs managed by the OAC, bi-monthly meetings between cognizant organizations are held during which changes are made or the existing list is simply revalidated. In any event, the list provides everyone with an audit trail that eliminates any reason for miscommunication as to what the user wants and what the technical community is working on. Table IV shows typical CR configurations and limits. The limits are "goals". This is, these are the goals required by the user which the technical community will try to establish but which may be unachieveable for a variety of reasons. example, flutter may limit aircraft speed and unsafe trajectories may limit store separation envelo The point is that every configuration should have a documented flight limit goal.

3.4 General Considerations before Initiating Separation Analyses and Testing

Now that the aircraft store configurations, captive carriage and separation goals, and priority to pace the schedule have been established and validated, one might be tempted to initiat separation analyses and tests. History has proven, however, that certain considerations should fi be addressed such as the following:

Paper and All Up Fit Test

As a minimum, fit checks performed using scale drawings, called "paper fit check", sho be performed to assess if the configuration is physically compatible before any analyses or other tests are initiated. The authors are familair with many cases where the technical community "assumed" the aircraft-rack-store configuration was physically compatible only to find out upon actually loading the store on the aircraft that there was a major incompatibility. This might not be a catastrophe were it not for the fact that these problems usually occurred after extensive, costly, and time consuming analyses had been completed. The OAC performs paper fit checks using the drawings contained in Aircraft/Store Interface Manuals (ASIM) developed by the Joint Technical Coordinating Group (JTCG) for tri-service (Army-Navy-Air Force) use, Reference (4). These manuals are now being converted into NATO AOP-12. There are three manuals: an aircraft manual, a store manual, and a suspension equipment manual. All drawings are to the same scale. The procedure for performing a paper fit check using these manuals is to superimpose the various store and rack drawings on the appropriate aircraft drawing at the desired carriage station. Figure 13 is an example of an ASIM drawing for the A-10. Note that the maximum deflection of all aircraft movable surfaces (such as flaps, landing gear, and access panels) are depicted. While these drawings are quite accurate, they are not precise. Two reasons are that some aircraft exhibit permanent deformations after being in service for some time and manufacturing tolerances (or lack thereof) of stores and the aircraft. The net result is that while a paper fit check might show close, but acceptable, clearance, an actual fit check might reveal negative, and unacceptable, clearance.

An all-up fit check using actual hardware is recommended at the earliest possible time. This is the best and surest way to avoid untimely surprises. MIL-STD-1289, Reference (5), was developed to standardize the fit test procedure and is constantly used by the USAF. Now that it has been converted into NATO STANAG 3899AA it is also being used by other Air Forces as well.

MID-STD-1289 recommends a minimum clearance between stores and adjacent rack/aircraft structure of three inches. The authors (who prepared the original MIL-STD) have received many inquires as to how this figure was established and what does one do if a lesser clearance is encountered? In the first place, three inches is a "guide". A greater clearance will not guarantee that aircraft-store interference will be eliminated during separation. The intent of establishing a minimum clearance was really aimed towards store designers. Nothing much can be done to eliminate fit problems between inventory stores and inventory aircraft. However, new stores should not be intentionally designed for less than three inches clearance with the intended aircraft. One might suppose that because of the MIL-STD there are no physical incompatibilities involving new stores. Unfortunately, the list is long and embarassing. One reason is that many store designers design the store to satisfy specific aircraft/pylon station requirements and do not take future USAF certification requirements into account. For example, after many years of developing and testing, a new store went into production. It was designed for three specific aircraft types and fit perfectly on these aircraft. Just after the store went into production, the user established a requirement for a fourth aircraft type. The store was subsequently determined to be physically incompatible on this later aircraft. In our view, store designers should design new stores for maximum possible commonality by considering not only stated requirements, but by also anticipating future requirements. Perhaps this example can be written off as bad planning. However, there are just as many cases where new stores did not even fit the aircraft for which they were designed. These cases can only be written off as bad engineering!

What does one do when paper and/or actual fit checks show less than three inches clearance between stores and aircraft? The choice exercised by the OAC in the majority of instances is to continue so long as there is a "positive" clearance. Recently, a new store was urgently required to be certified on an aircraft. Upon delivery of the store (an inventory store) to the test site, and upon performing an actual fit test, a clearance of less than one inch was recorded between the store and the aircraft's fully deflected flap. Even though the clearance was much less than desired, the extent of possible damage to the flap if the store were to make contact during separation was assessed and was determined to be quite low. Accordingly, the decision was made to continue with the program but with great caution. In fact, several test points were added to the program to reduce risk. The program was completed without incident and post flight analyses showed that had the initial store to flap clearance been three inches instead of less than one inch, the separation envelope would only have been increased by about 10 knots. The point to be made is that a MIL-STD cannot always drive a go/no-go decision. Program requirements should be meshed with good engineering judgment and then the go/no-go decision will almost invariably become self evident. In this last example, it was to "go" despite less than three inches clearance to start with. Lastly, if the minimum store-to-aircraft clearance is more than three inches, one should not assume there is no cause for concern. Perhaps the monitoring level between missions can be a little less, but close monitoring must prevail at all times since a large static clearance at one speed can completely disappear (and result in store-to-aircraft contact) at another speed.

Functional Analyses

As in the case of paper and actual fit checks, it is essential that functional analyses for stores that require an electrical interface with the aircraft be performed as early as possible. As a minimum, functional analyses should be performed before any compatibility analyses or other testing is initiated. In functional analyses, the store power and signal requirements are meshed with the aircraft output power characteristics. Usually, functional analyses will either validate functional adequacy or uncover functional inadequacies. If functional inadequacies are discovered, their nature and scope may preclude further work until a solution is devised. Ideally, functional analyses should be closely followed by an actual functional check on the aircraft. In most cases where an inventory store is being certified on a inventory aircraft, an actual functional check is easily arranged. In fact, functional checks should be performed in conjunction with fit checks in accordance with MIL-STD-1289.

It may be obvious that functional analyses (like paper fit checks) should be performed before initiating costly and time consuming analyses and testing in the other compatibility disciplines. However, our experience has been that many cases of functional inadequacies were uncovered after all analyses and ground testing had been completed and flight testing was about to begin. In most of these cases, engineers either never thought to check (they "assumed" there was no problem) or the engineers who did check were in a different part of the organization and never communicated with the rest of the organization about the problem. Consider the following examples:

- An actual functional check was made for a rocket launcher carried on a parent pylon rack on one station of a certain aircraft before beginning compatibility analyses. The functional check was successful. It was assummed that since the launcher was functionally compatible on one station, it would be compatible on other required stations and, therefore, other stations were not checked. At the beginning of the flight test program, long after analyses had been completed, an electrical continuity check of the aircraft was made to ensure that an electrical signal was being sent to the ejection rack where the rocket launcher was mounted. Nothing more was done even at this late stage. The flight test program began and captive compatibility and launcher jettison testing were successfully completed. Now the program was ready to move into the rocket firing phase. On the first mission the pilot selected the proper cockpit switchology to fire rockets, depressed the trigger, and nothing happened. This now became a high visibility problem. Extensive functional analyses were performed on the problem pylon station and subtle differences between pylon stations were uncovered. Rockets were fired by "fooling" the aircraft stores delivery system into believing it had a store mounted on a multiple carriage rack when in fact it actually had a launcher on a parent pylon rack! While this allowed the program to be completed, one can imagine the confusion the pilot would have in an operational environment with such an arrangement. Eventually a software modification was performed to return the aircraft to normal switchology.

- An ECM pod was required to be carried on an aircraft. All compatibility analyses and testing were completed and flight testing was ready to begin. The fit check was satisfactory. The functional check revealed that the aircraft did not have the electrical capacity to power the pod. The certification action was cancelled with a major disruption to the flight test community who had blocked out time and resources to support a considerable number of missions.

Clearly, paper fit checks and functional analyses must be performed as early in the compatibility cycle as possible. In all cases, these should be exercised (such as rocket launcher jettison and rocket firing) using aircraft cockpit switchology. Only in this way can surprises in the functional area be avoided when they are least expected.

Store Strength

Not long ago a program to certify a finned firebomb on an aircraft was completed. The carriage and employment goal was 600 KCAS. Paper fit checks were satisfactorily performed (functional analyses were not necessary due to the absence of an electrical interface). Wind tunnel tests were performed to acquire necessary data (such as for aircraft stability and control, aircraft loads, and store separation) and extensive analyses (such as for aircraft flutter) were performed to establish captive carriage and separation envelopes. Subsequently, on the first captive compatibility mission, during which aircraft handling qualities and aircraft/store structural adequacy were being qualitatively evaluated, the store fins failed at 400 KCAS. Research, after the fact, revealed that this same store had similar problems on other aircraft. In short, had store strength been properly addressed earlier, the scope of wind tunnel tests and other analyses, and the flight test program, could have been reduced. In this particular example, it was "assumed" (erroneously) that the store was "Government Furnished Equipment" and, therefore, was structurally sound throughout the intended flight envelope.

Most new stores in the United States, except for approved deviations, are designed in accordance with MIL-A-8591 (NATO STANAG 3441), Reference (6). Stores can be designed for carriage on a specific aircraft (Procedure I) or for carriage on generic aircraft (Procedure II). In the OAC, stores are required to be designed in accordance with Procedure II since this ensures that the store can be safely carried on any known aircraft. Procedure II uses conservative airloads coupled with an aircraft inertial envelope that encompases worst case boundaries of all inventory aircraft. If a store has been designed in accordance with Procedure II, no further checks on store strength are required.

The advantage of designing stores in accordance with Procedure II can be illustrated with the following example: A new store that had been designed in accordance with Procedure I showed that it could not be carried on an additional new aircraft type without limiting the aircraft envelope unless the store was redesigned. The reason this situation occurred was that the contractor designed the store in accordance with Procedure I, since the user only required the store to be carried on one type of aircraft. Unfortunately, as has been recorded earlier, the user later added another aircraft type: one that had a larger inertial/maneuvering envelope than the original aircraft. Structural analyses showed that the store would either have to be redesigned or the aircraft acceleration envelope would have to be reduced. It was decided to reduce the aircraft acceleration envelope since the cost to redesign the store was considered to be prohibitive. The moral, of course, is that had the store been designed in accordance with Procedure II it would have been over designed for carriage on the original aircraft but it would have been worth it. Invariably, the user will want most inventory stores to be carried on most aircraft. Designing the store in accordance with Procedure II is the recommended approach to avoid future problems. Only special mission stores such as mines or torpedoes should be designed in accordance with Procedure I and, even then, only if carried on a limited number of aircraft types.

In summary, the structural strength of the store must be known or should be established ·y in the compatibility cycle. This will ensure that captive carriage and separation analyses and tes are not needlessly performed outside the speed envelope that the store can be safely carried.

Captive Carriage Envelope

Given that the store fits, will function, and is strong enough for carriage within the desired flight envelope, a qualitative assessment should be made of the likelihood that the aircra itself can safely carry the store (from aircraft load, stability and control, flutter an other suc standpoints). The flight limits for analogous stores and store configurations which are already certified should be reviewed and compared against flight goals for the stores and store configura in question. For example, assume that it is desired to certify the BLU-80 store on the F-16 to 60C and 7g positive symmetrical load factor. One would now see if there is an analogous store to the B 30 store on the F-16. The MK-20 Rockeye would immediately come to light as being analogous. Both us e same basic body and have similar mass properties. Next, one would see if the certified flight envelope is equal to or greater than the flight limits desired for the BLU-80. If they are, separation analyses may be scoped to consider the entire flight envelope with reasonable certainty. On the other hand, if the flight envelope is restricted it would be pointless to perform extensive separation analyses at flight conditions outside the expected captive carriage envelope.

When a clear analogy cannot be established, or when a restrictive flight envelope is anticipated or suspected, it is desireable to complete captive carriage analyses and testing before starting separation analyses. Frequently, however, schedule constraints force simultaneous separation and captive carriage analyses. In this event, one has no choice. But to reiterate, use the analogy approach whenever possible in an attempt to qualitatively establish a preliminary captive carriage envelope and to scope the separation program. It would be wasteful to perform separation analyses for a store up to the desired flight limit goal only to later learn that the captive carriage flight envelope was several hundred knots less due to aircraft stability and control, load, or flutter problems. It would be especially embarassing to learn late in the program that the store being certified was analogous to a certified store having much lower limits. It has happened too many times in the past. We are striving to educate others so that it will not happen again.

The reader is urged to review References (7) - (9). These references are quite important in our opinion. Reference (7) details the responsibilities of all organizations involved in the aircraft/store certification process and outlines the procedures to be followed for conducting aircraft/store compatibility programs. Readers from other nations may find it instructive to compare USAF organizational procedures and responsibilities with their own. References (8) and (9) fall into the category of required reading in the our opinion. These references define and provide procedures for formulating and conducting ground and flight tests/analyses in support of aircraft/store compatibility programs. These references also contain an array of useful supporting material such as approved aircraft/store terminology and a bibliography of government publications, standards, and specifications.

4.0 STORE SEPARATION PREDICTION TECHNIQUES

After considerable research, the authors believe that all of the store separation prediction techniques in use throughout NATO have already been thoroughly discussed in an array of published literature. For this reason, it was decided to present no more than an overview since this report is intended to be used as a guide for the new store separation engineer and management personnel. An extensive list of references is provided for those readers who wish to research individual store prediction techniques in the detail needed to actually use any or all of them.

4.1 Review of Types of Prediction Techniques

Methods designed to predict store separation motion may be categorized into three broad groups: theoretical, empirical (or semi-empirical) and analogy. These three groups are distinguished by their different aerodynamic approaches. Each approach offers advantages and disadvantages to the store separation engineer. The trajectory problem may be considered as two interrelated problems; aerodynamic and dynamic, that may be coupled to each other or treated separately. Generally, theoretical approaches utilize the solution of the fluid equations which can be coupled or uncoupled to solve the equations of motion. By coupling the fluid equations to the equations of motion, one can solve for the new attitude of the store at each time step in the store trajectory and then use this new aircraft/store physical relationship to calculate a new flowfield. Using the new flowfield parameters, the aerodynamics may be updated. Conversely, in the empirical approach, a specified survey of points throughout the flowfield can offer the aerodynamic information which is recalled via table look-up when the store moves to a new point (and/or attitude). More recent predictive methods offer the option of coupling or decoupling the influence of aircraft/store mutual interference at each time step. Empirically or semi-empirically derived aerodynamic solutions are predominately used decoupled from the equations of motion solutions. The grid data based approach is an excellent example which is discussed in a following section. Store separation prediction by analogy relies on past experience with a store of similar aerodynamic shape and mass properties and using its known separation characteristics to predict the new store's movements. Each of these generic methods will be discussed in detail, followed by sections explaining how each nation utilizes them.

4.1.1 Theoretical Prediction Methods

Purely analytical predictive methods used today to study store separation trajectories are applications of various paneling methods that solve the linear Prandtl-Glauert equation. A general three dimensional boundary value equation is then solved for the configuration of interest. The equation governs incompressible and linear compressible flows in both subsonic and supersonic regimes. Further, the assumption of inviscid flow applies. These panel methods differ from the more complete nonlinear potential flow formulations that govern the transonic flow regime. These nonlinear potential flow formulations (that is, transonic small disturbances and full potential flow) retain terms to improve the resolution of shock waves and to more readily determine when the equation changes its nature; that is, elliptic or hyperbolic. Although these equations are more applicable to the problems of concern in store separation testing, they are, computationally, more difficult to solve.

Paneling methods have envolved since the early seventies to the point where rather complex configurations can be addressed. A major advantage of these paneling methods is that, unlike solutions of transonic full potential or other nonlinear "higher" forms of the Navier-Stokes equations, they do not require a field grid for numerical solution (much less an adaptive grid needed for trajectory studies). This frees these schemes of geometric limitations that limit the nonlinear methods to more simple configurations. Additionally, at this time, no methods exist to provide a coupled trajectory solution using these higher nonlinear schemes. Paneling methods have evolved from earlier "lower order" versions that feature constant singularity strengths (or linear variation in one direction) on each panel. Higher order versions such as PAN AIR are distinguished by non-constant singularity strengths or "composite" panels that allow a linear source and quadratic doublet variation on each panel. These improvements have helped to make panel solutions less sensitive to panel spacing and density allowing more complex configurations to be studied. The use of composite panels has allowed singularity strengths to be made continuous on a configuration. This has significantly reduced the potential for numerical error, particularly for supersonic flows. A feature of PAN AIR is the implementation of the KUTTA condition allowed by the use of the composite source-doublet panel. This makes the computed flowfield relatively insensitive to modeling detail at the trailing edge. The code also features an expanded treatment of wake modeling which enhances its use for lifting surfaces. The reader is referred to Reference (10) for a detailed discussion of the feature of PAN AIR.

References (10) and (11) present comparisons of PAN AIR predicted results with experiment for both subsonic and supersonic flows. Data comparisons were made at various subcritical subsonic and supersonic Mach numbers. Results show excellent agreement except in the region where nonlinear effects are to be expected. The Prandtl- Glauert equation is valid for subcritical flow about slender bodies and thin wings at arbitrary subsonic or supersonic Mach numbers where flow discontinuties are not present. While PAN AIR and other paneling methods can provide trajectory solutions for relatively complex configurations in subcritical flows, numerical gridding techniques have not as yet matured.

The application of paneling methods such as PAN AIR, NEAR, Reference (12) and others can be very useful in the study of store separation characteristics as long as the limitations of the methodology are kept in mind. These codes can offer a first look at details of the flowfield that normally are not obtainable without special, costly, experimental test techniques. Additionally, the majority of "real world" store shapes are complex and pose extremely complex modeling problems. Although "higher order" panel methods may now be able to accomodate these more complex shapes and configurations (such as multiple stores carriage), these real world configurations only further aggravate the nonlinear aspects of the aerodynamic problem.

A first step in investigating a new store for release characteristics lies in understanding the store's freestream aerodynamics. Preliminary trajectories can be computed for the store using this data with flow angularity or with grid data from very similar stores (if available) to determine if more elaborate testing is necessary. Preliminary data can possibly be acquired by examining the freestream aerodynamic data from similarly shaped stores. The OAC and AEDC have jointly developed a freestream stores aerodynamic data management system that contains over sixty stores with a wide variety of characteristics. This system is automated for data retrieval with a number of features for manipulation of the data. The data base is described in Reference (13). The data base has proven invaluable in a number of instances in supporting first order trajectory studies on short notice.

A number of semi-empirical aerodynamic estimation codes are used in conjunction with the freestream data base. These codes augment experimental data or provide a first order estimate when data are not available. These codes continue to be improved and currently those most used are DLCODE Reference (11), MISSILE DATCOM Reference(14), NSWC Reference(15), and NSRDC Reference (15). These codes are used to produce freestream aerodynamics to be used with flow angularity and grid data as inputs to six degree of freedom trajectory programs. The codes require geometric inputs and are relatively simple to use depending on the program. In addition, AEDC has developed an executive selection program that assesses up to eight separate estimation programs with logic designed to select the particular code that can best compute a particular aerodynamic coefficient for the geometry and Mach number/angle of attack range of interest. In the authors' view, attaining this capability should be a requirement of any agency desiring to establish a comprehensive stores compatibility program. Most semi-empirical codes are relatively simple to use for first order estimates of release behavior. Higher order solvers (such as paneling methods) or Euler solvers, are more difficult for the using engineer to apply. However, many are evolving rapidly into more user-friendly codes. Until these codes are generally available, semi-empirical estimation codes will continue to be used and improved.

Before closing this section on theoretical methods, it should be noted that Reference (10) indicates that methods which make use of panel surface geometry are under development for solving non-linear transonic problems. Many believe that codes with a "transonic panel" method may be available in the future. The geometric versatility of such a paneling method may make this approach, in some cases, very competitive with future more elaborate nonlinear solutions that will use field grids. Further, the rapidly accelerating capability of Computational Fluid Dynamics is being turned to solution of the transonic store separation problem. Basic research is well underway in the USAF, in the academia, and in aerospace companies around the world. The USAF's Armament Laboratory has chosen the Euler formulation as the solution algorithm. This avoids the limiting assumptions of small disturbances and the restrictions of slender body store and relative weak flowfield gradients. The Euler algorithm will be solved numerically using a contour-conformal grid scheme that has the advantage of flexibility in concentrating the grid in an area of the flow where strong gradients occur and is applicable to any aircraft/store configuration: Single and multiple stores carriage, slender and non-slender bodies, and arbitarary shapes will also be incorporated. Additionally, dynamic grid concepts will be applied to the store separation problem. Contour conformal grids will be allowed to dynamically adapt to the movement of the store as it separates from the aircraft. Currently, the grid generation and Euler solving computer program have been derived by the Armament Laboratory and are being checked out using simple store shapes. Dynamic gridding algorithms are just now being developed. Wind tunnel testing designed to provide data for method validation will be performed over the next several years. Near term, the development of "transonic surface paneling" methods will significantly aid the study of transonic store separation as higher order solvers continue to be developed. Yet, for the foreseeable future, empirically derived data will continue to be a principal source for the "aerodynamic" solution of the separation problem.

4.1.2 Empirical and Semi-Empirical Methods

Despite the recent advances in computational techniques, the authors believe that wind tunnel testing is, and will remain for several years to come, the most reliable prediction technique that can address the transonic store separation problem. Wind tunnel testing techniques used in understanding store separation events are well known. References (16) through (20) present a concise review of the various techniques and, therefore, are reviewed herein only briefly.

Selecting the approach for the store configurations of interest to yield the most reliable and cost effective data is the most important consideration in planning a wind tunnel test. However, designing a test to acquire data that may be later extended to other configurations, or utilized beyond its initial intended purpose, is another very important consideration. Some wind tunnel testing techniques obviously offer this advantage while others do not.

There are basically four wind tunnel methods that continue to be used to predict store separation trajectories. The USAF has used all four techniques in support of a variety of programs. These four techniques are: Captive Trajectory System (CTS), Grid (flowfield data base), Flow Angularity (flowfield data base) and Freedrop. In addition, two other more recent wind tunnel based techniques are discussed that offer alternative approaches. These are: Installed Carriage Loads Derived Grid Flowfield and the Influence Function Method.

- CTS:

Within the United States there are five wind tunnels equipped with articulated dual sting arrangements that support CTS testing. Of these five tunnels, four are transonic tunnels while the other is a supersonic tunnel. Practically all of the store separation testing performed by the USAF is accomplished in the AEDC four foot transonic wind tunnel (called 4T). The principle of the CTS is essentially comomon to all wind tunnels. The AEDC 4T facility is typical and can be used to cite advantages and disadvantages. The articulated dual sting arrangement used for store separation studies is no more than a system that supports the aircraft model on one sting, with limited movement, while the store model with an internal balance is mounted on a separate sting capable of commanded movement in all six degrees of freedom. Aerodynamic forces and moments on the store are measured by an internal strain gage balance that may measure from five to six force and moment components. The aerodynamic data measure by the balance is fed to a computer during the test run. These forces and moments are combined with other required data such as store mass property characteristics (weight and center of gravity), ejection forces, rate damping forces and moments of inertia, which are not measured and which are needed to solve the equations of motion and predict the store's next position relative to the aircraft for a simulated increment in time. Through a closed loop system, the new position in time is fed to a positioning device which then commands the model sting to move to a new position in the tunnel. The cycle is then repeated automatically to obtain a complete trajectory. Figure 14 shows an F-111 model in the AEDC 4T facility with a store mounted on the CTS sting. This figure illustrates quite well the extended movement capability of the CTS sting. It may be noted that a one second trajectory normally takes about ten minutes (Reference (18).) However, as a result of a concerted cost reduction program, AEDC will be able to reduce this time in the future (Reference (21).)

CTS offers the primary advantage of most closely measuring the actual forces and moments (within general wind tunnel constraints) during the store separation trajectory that are the result of the store's actual attitude and position. Furthermore, within the assumption of quasi-steady flow that is common to all wind tunnel testing of this type, CTS can more closely simulate factors such as varying aircraft load factors and maneuvers, varying ejection force parameters, varying store thrust and a variety of other parameters that obviously other methods, such as freedrop, cannot. Its advantages over other methods that "aerodynamically" map the flowfield (such as grid and flow angularity) is that it measures the aerodynamic forces and moments at the precise point in the trajectory, and at the precise calculated attitude of the store. This technique provides the most accurate experimentally determined aerodynamic data for a position in the trajectory; but has some dramatic limitations.

CTS is not designed to provide the user with a useful data base for examining a large number of individual trajectories off-line. This off-line capability is needed to understand the sensitivity of store release to many different variables such as Mach number, angle of attack, changes in store mass and inertia characteristics, fin deployment times, aircraft dive angle (load factor), ejection performance, and many other parameters that require many individual simulations. These large numbers of simulations cannot be economically completed in the wind tunnel. Although CTS can offer the advantages of an "on-line" trajectory simulation that can shorten analysis time (given the existence of models and a timely entry in the wind tunnel), this can be offset by an even more far ranging requirement for an aerodynamic flowfield data base that can be used in the future. Future development or product improvement may alter mass and inertial characteristics of a store or other important variables. These changes and the effect they would have on the separation trajectory would be very difficult to isolate using CTS data from a previous configuration. Furthermore, no capability would exist to match predictions to actual flight test conditions. This tool would be required in order to identify potential design changes that may become apparent during flight testing. CTS data acquisition can also be hampered by hardware problems. The dual sting arrangement has been designed to terminate the trajectory whenever the store or sting contacts the aircraft. For some aircraft/store configurations and stores that exhibit large angular motions, the trajectories may be terminated too quickly - before any useful data can be acquired. While this is not an insurmountable limitation, the separation engineer must be ready to alter trajectory data inputs during the wind tunnel test to assure longer trajectories for better study or live with the short trend trajectory information available from the test runs. Practical limitations on CTS equipment in the past has resulted in trajectories being terminated due to the linear motion of the store sting positioning device. Recent improvements made by AEDC in the software that controls the CTS apparatus motion allows the CTS movement to more closely parallel the actual store trajectory. This has significantly reduced the occurrance of premature termination of trajectories due to sting/store grounding. Again however, CTS trajectories for stores that exhibit larger angular motions may still terminate too soon to provide useful data.

- Grid

The CTS can be used to provide wind tunnel data in the CTS mode or the grid mode. The grid mode is essentially a flowfield mapping technique in that the store sting is positioned automatically to preselected and preprogrammed positions and attitudes with respect to the aircraft model. The store/balance combination then measures aerodynamic coefficient data at each point. During testing of this type, a matrix of coefficient data is obtained through a region of the aircraft flowfield that can be expected to encompass the subsequent trajectory path for a particular configuration. Figure 15 shows a typical grid. The measured values represent total aerodynamic coefficients of the store as a function of the store's position and attitude at a particular point in the aircraft flowfield. By subtracting the store's freestream aerodynamic coefficients (measured for the same store model at the same attitude outside the flowfield of the aircraft) from the total aerodynamic coefficients, a set of interference aerodynamic coefficients can be calculated as a function of position and attitude within the aircraft flowfield. The matrix of interference coefficients becomes a data base available for subsequent trajectory calculations. These interference coefficients are recombined with freestream aerodynamic data during each time step of a trajectory calculation to determine a total aerodynamic coefficient applicable for that store's position and attitude within the aircraft flowfield.

The basic advantage that the grid technique offers is its implicit versatility for future studies. On-line wind tunnel test time required for computation of trajectories using the full CTS mode is not used in the CTS grid mode to gather a larger aerodynamic data base that can be used for further studies later. A larger, more comprehensive, set of trajectories can be generated more economically and efficiently by allowing the store separation engineer the flexibility of careful study of trajectory sensitivity to various parameters outside of the high cost environment of the tunnel test section. For certain configurations such as stores with deployable fins, this approach may be far more economical and much more practical than a comprehensive CTS test of a model with changing configurations.

For a given aircraft/store configuration the aerodynamic loads acting on the store are functions of the aircraft Mach number, angle of attack and sideslip angle, and the store's relative position and attitude with respect to its carriage position. A comprehensive set of aerodynamic interference coefficient data as functions of all these variables would require a lengthy wind tunnel test program as well as a trajectory generation computer program set up to sift through all of the data for the appropriate values and to interpolate or extrapolate as necessary. Such a program would require a high speed computer with a large storage capacity. The apparent disadvantage of the grid technique in requiring a data sift program can be offset by judiciously selecting what grid data needs to be taken. Reference (22) describes a joint wind tunnel study between the OAC and AEDC. This study concluded that interference aerodynamics varies considerably more with vertical displacement than with lateral or longitudinal displacement and that store orientation in an axis within the grid volume generally has a minimal (second order) effect on the interference aerodynamic coefficients. In some instances of stores with large planform areas, a second order influence of store pitch on the interference coefficients may become important. References (19) and (22) expand on the significance of the study on planning a grid wind tunnel test for a new store. Experience with limited grid testing though, has demonstrated excellent correlation with full CTS trajectories for most store separation studies conducted over the past several years by the OAC.

A number of references are listed in the work mentioned above which substantiate the use of limited grid for complex aircraft flowfields and store shapes. Additionally, there are a number of techniques that have evolved over the years that can aid the store separation engineer in optimizing a grid survey. In the case of multiple carriage racks, the displacement for stores ejected at an angle from the vertical may be easily estimated and the resultant trajectory used to define the vertical and lateral displacements at desired grid points. Careful attention to structuring the configurations to be tested and the order in which they are tested can help to streamline testing by treating each side of the aircraft model as a separate flowfield. This allows the store separation engineer the ability to minimize tunnel shutdown, model changes, and start up times during a test.

- Flow Angularity

A second commonly used method for determining interference flowfield aerodynamics is the technique known as flow angularity. Aerodynamic data is normally obtained by using a velocity probe attached to the CTS sting apparatus in place of the store/sting combination. The velocity probe is then used to measure velocity components at various locations in and around the aircraft flowfield within a volume that is expected to included the store's anticipated trajectory. From this information, local flow angles of attack are determined generally at the nose and tail of the store. This information is used with freestream lift curve slope data to generate the interference coefficients rather than measuring the interference coefficients themselves. Two approaches are generally employed when utilizing a velocity probe. The first approach, as discussed in References (19) and(23), is to measure flowfield effects with the store installed in its carriage position. The second approach is to measure the initial store loads along the centerline of the store as it if were installed on the aircraft. Although neither approach is a true representation of the interference flowfield both can provide a first order answer to store trajectory studies. The first approach incorporates a partial influence of the store upon the interference flowfield while the second approach may be more versatile in dealing with a larger class of stores of various shapes and planform areas. The greatest advantage of this second approach is its adaptability to providing quick answers for stores that have not been wind tunnel tested. Using this approach however, requires a thorough understanding of the freestream aerodynamic characteristics for the store in question, including the relative contribution of the nose and tail segments. This data can be acquired from wind tunnel testing or approximated by aerodynamic estimation computer codes. Normally, the variation of aerodynamic forces with angle attack and center of pressure data is required. This methodology generally allows a greater degree of flexibility in modeling the interference flowfield interaction due to fin control surface motion of fin deployment for complex stores. This is the case for modeling the damping of free floating control surfaces (such as canards). A detailed description of the approach can be found in Reference (19). It may be noted that although the normal approach for acquiring flow angularity data is through the use of a velocity probe attached to the CTS sting, some work has been done to explore the use of a laser doppler velocimeter in measuring local transonic flowfields. The real advantage in using the velocimeter lies in removing any physical interference attributed to the probe itself. Finally, techniques have been developed for extracting flow angularity data from grid data for certain stores. By using measured freestream aerodynamic data, one can extract local flow angles and produce a data base of local flowfield angles that can be used to solve the aerodynamic interference problem for other stores. A newer technique that will be discussed later is an extension of the flow angularity approach.

Influence Function Method

Since wind tunnel testing still offers the most accurate method for addressing store release problems, the large number of store/aircraft and flight conditions involved in certifying stores mandates that methods be developed to improve the cost-effectiveness of wind tunnel testing by extending test data beyond the stores to which the testing was initially geared. The flow angularity technique discussed previously has been recognized for some time as a useful approach for this reason. The Influence Function Method (IFM) described in References (24) and (25) is a natural extension of this method - from two store elements (nose and tail) to any number of store elements - with some important differences. The flow angularity technique uses freestream values of the normal force coefficient slope and angle of attack for the nose and tail plus assumed locations of the nose and tail centers of pressure to calculate moment coefficients. The IFM determines these coefficients by traversing the store model through a known flowfield longitudinally, aft to forward, where the local angle of attack is known. At each point in the traverse, the aerodynamic forces and moments are measured generating a series of equations. By matrix inversion the influence functions themselves are calculated and the store is calibrated to a known flowfield. Conversely, a "calibrated" store can be passed through an unknown flowfield to determine the local flow angle along a tranverse line during a wind tunnel test to solve for the unknown flowfield. In completing this method, the store of interest can then be immersed in this flowfield analytically along that tranverse, having been calibrated previously to a known flowfield. The aerodynamic coefficients can then be solved by matrix multiplication. This methodology has been successfully used for supersonic flowfields with excellent results for single carriage stores at various vertical distances from the parent aircraft. Investigation of the technique's application to subsonic flows is still underway as is also the extension of the technique to the other aerodynamic coefficients (yaw and roll). Preliminary findings tend to indicate comparable results can be achieved for subsonic flows.

The obvious disadvantage of the IFM lies in the calibration of the store in question. The general approach for supersonic conditions would be calibrating the store experimentally by passing it through a known flowfield such as an oblique shock wedge flow. The requirement for a wind tunnel test is an obvious disadvantage. Calibration using analytically derived flowfields produced by paneling methods such as Pan Air has generated accurate influence function calculations. Reference (26) (unpublished) has also demonstrated the reasonability of using semi-empirical aerodynamic estimation programs, such as DL CODE, that have been modified to superposition simple flowfields on the store model within the code. Using the same traverse logic, calculations of the influence functions were made using the code generated coefficients. Reference (26) reports very good agreement with other calculations of influence functions and subsequent comparisons of trends in predicted and measured aerodynamic coefficients for a GBU-15 store in an F-15 flowfield. The biggest disadvantage of this particular approach, in the authors' view, lies in the fact that such prediction codes have inherent limitations in predicting shock strengths. Consequently, local flow angles may show large discrepancies in these regions.

- Freedrop

The fourth empirical wind tunnel method in use today is the freedrop method, also called dynamic drop. In this approach, scale store models, constructed to obey certain similarity laws, are released from the aircraft model in the wind tunnel. High speed orthogonal photography is used to record the event. The film is read to extract time position data that can be used to understand the separation events and to assess the relative risk of flight testing. Static aerodynamic forces and moments acting on the store are properly scaled when the model geometry and flowfield are matched to full scale flight conditions. The accelerations of the store model will be similar if the total forces and moments, mass, center of gravity, and moments of inertia are also properly scaled. In achieving this scaling, the model is scaled to one of three scaling laws; heavy, light, or Froude. Selection of the most suitable scaling law depends on the nature of the separation problem, those parameters of particular interest to the store separation engineer (which needs to be accurately known) and the capabilities of the facilities available.

Reference (18) outlines the dynamic scaling principles involved in freedrop testing. Proper scaling requires linear geometric scaling of aircraft and store models from full scale to model scale. Also required is linear and angular acceleration matching for both aircraft and store models. Relationships for the ratio of model scale and full scale values for time, velocity, Mach number, moments or inertia, ejector forces, and related parameters are calculated as power functions of the scaling factor.

If compressibility and viscous effects are matched, then aerodynamic coefficients are matched between model and full scale. These premises lead to the scaling relationships that are known as Froude scaling: so named because the velocity scaling is equivalent to the hydrodynamic Froude number. The reduced Mach number at model scale resulting from Froude scaling, however, generally only insures aerodynamic coefficient equality for low subsonic (less than 0.8 Mach) full scale flight conditions.

Assuring that the aerodynamics are properly matched requires that Mach number be matched at the expense of another parameter. Those techniques that maintain Mach number equality are known as "heavy" and "light" scaling. Heavy model scaling results in an increased velocity requirement over that of Froude scaling and with all else being equal, the required mass of the model is larger than that required for the Froude scaled model. Because the velocity ratio has been relaxed, heavy scaling fails to account properly for induced angle of attack or aerodynamic damping effects on angular motions. Similarly, linear motion is also affected by induced angle of attack variances. The amplitude of angular motion will be too large due to under damped motion.

Light model scaling can be used when proper angular motion response is of major importance. Light model scaling is so named because the mass ratio is maintained to that of Froude scaling and retains the velocity ratio simulation along with Mach number by assuming that the gravitational constant within the wind tunnel test can be arbitrarily increased. In reality, the gravitational constant within the wind tunnel cannot be changed. The deficiency in the required gravitational acceleration called for by light model scaling can be corrected by artifical means. The use of magnetic fields or use of the aircraft model sting apparatus to accelerate the aircraft model away from the store at store release, and the use of increased ejection forces are typical methods that can be used.

Of the various scaling laws, heavy model scaling, in our view, is the predominant method used by most agencies throughout NATO. Because of the low subsonic requirement for Froude scaling, the method becomes unsuitable for the majority of work that centers around transonic flowfields. While heavy model scaling results in under damped angular motion of the store during separation, the trend usually results in a conservative approach to safe separation studies. References (16) and (27) generally indicate that heavy model scaling agrees favorably in angular motion in full scale trajectories and very well in linear motion since the ratio of aerodynamic forces to gravitational forces is maintained. Light model scaling generally results in deficient vertical store separation distances while agreeing much closer to full scale trajectories in angular motions. Reference (17) reports that a correction to vertical acceleration can be made by altering the ejector force. This requires some a-priori knowledge of the flowfield that can be used to tailor this technique to the test. For highly complex configurations where little or nothing can be realistically assumed about the flowfield, such a technique would not be very useful. Consequently, the literature surveyed tends to recommend heavy model scaling as the preferred method for most modern day studies.

Selection of the appropriate scaling method is dependent on the separation problem and the experience and preference of the using engineer. However, dynamic drop offers certain advantages and disadvantages in comparison to other trajectory acquisition methods. Realistic considerations need to be understood in deciding whether this approach over another is advisable. Reference (18) elaborates on these factors in detail. Some advantages and disadvantages of using freedrop are summarized in the following paragraphs.

- Freedrop testing generally offers the best (if not the only) approach where model size or shape precludes a suitable store-balance-sting combination design. Modifications to the rear part of store models to accomodate stings can alter the store aerodynamics (such as static margin). Freedrop testing eliminates this problem. In cases where stores are required to be released from internal aircraft bays, freedrop testing can offer the best solution to the problem. Freedrop is particularly suitable for unstable stores where tumbling motion can be continued without the constraint of CTS sting limitations/mechanical contraints. Finally, freedrop testing allows studying multiple stores releases from racks in the ripple mode.

- The greatest disadvantage to freedrop testing lies in its cost and the rather limited use of the data for future study. Data reduction is also a lengthy process. The nature of freedrop testing is such that the store is usually destroyed. The model is normally captured in screens after release but only to salvage the model for refurbishing for later testing and to prevent wind tunnel damage. Normally, one model is used for each drop. The cost of model fabrication may easily reach a sizable percentage of the total test cost. Tied also to the cost is the fact that the tunnel is shutdown after each drop in order to retrieve models and reload the aircraft model with new store models. Normally, one to two drops are made per hour, and while "air on" time is short, tunnel occupancy is considerably lengthened. Incidentally, the model sceens generally increase required tunnel total pressures and hence, increased power costs for higher Mach numbers.

- Model fabrication, particularly with heavy model scaling, can be difficult in obtaining the correct scale of moments of inertia, weight, and center of gravity simultaneously. The requirement to use high density materials such as tungsten, gold and other expensive metals or alloys can drive costs up further, plus create fabrication problems. Engineers should consider allowing a tolerance in modeling the store mass properties - saving design time and the possible selection of less costly materials and machining. Ejection mechanisms can similarly produce problems in modeling. Testing may not be possible with certain full scale ejection forces due to practical limitations in model ejector designs.

- Finally, a fundamental shortcoming of freedrop is its inability to address releases under active guidance or with axial thrust. Furthermore, the method is not particularly suited to maneuvering release or diving flight although methods have been developed for correcting vertical and axial displacements due to the load factor and bank angle associated with the maneuver (Reference (28).) Summarizing, freedrop methods (particularly using heavy model scaling laws) produce very good agreement with full scale trajectories and in some cases offer the only viable experimental technique. The technique has major drawbacks in the costs associated with this type of testing, the unsuitability of the data for future study, and its limitations to certain types of separation problems.

A Note on Model Scale for Wind Tunnel Testing

Perhaps the single most prominent problem associated with wind tunnel trajectory testing techniques lies within the realm of model scaling. Generally, the wind tunnel test approach is valid for the simulation approach in use today. Under the assumptions of quasi-steady flows, the aerodynamic behavior of the store within the flowfield is tempered only by Reynolds number and the fidelity of the model and support system to produce as near as possible the full scale external store shape. Realistically, however, the high cost of wind tunnel testing favors the smaller tunnels and consequently, the CTS and grid testing approaches used by the OAC have been designed around a 5% scale collection of store models. This standardization of scaling has contributed to a substantial savings in model fabrication costs since many store programs involve many different aircraft types. It may be noted that the OAC also maintains 5% models of practically all inventory USAF fighter aircraft. The F-111 model is the only one which is not standardized. It is a 4.7% model and this does cause store model problems. Five percent scaling is suitable to the AEDC 4T tunnel but creates a challenge in minimizing loss of store detail at this scale. For example, sophisticated guided bombs possess antennae, umbilical fittings, conduits, and other protuberances that are extremely difficult to model at this scale. More importantly, these same types of stores may have lifting surfaces with airfoil shapes. Modeling of these surfaces is often restricted to flat plates with shaped leading and trailing edges. Correct alignment of these surfaces is also difficult at these scales. Additionally, stores with canards or other control surfaces designed to "trail center" or "float" freely during carriage and the first few seconds after release before being engaged are extremely difficult to model effectively. The engineer often must assume the worst case condition exists with these surfaces locked. Alternatively, freestream data collected for a larger scale model may be incorporated to estimate the deflection of these surfaces within the aircraft flowfield. Mating some store models to the sting balance combination may become very complicated at 5% scale. Often some modification has to be made to the store afterbody to be able to accept the balance. Furthermore, sting interference effects on store aerodynamic characteristics, particularly at transonic Mach numbers for stores with boat tail after bodies, can be significantly affected by sting-to-model base diameter ratio. While these effects can be alleviated somewhat by prudent sting design, there are important model design considerations that the using engineer should keep in mind when dealing with small model scales. Testing has shown that attention to minute model detailing to the maximum extent can improve small scale results with regard to full scale or flight test results. Details such as store openings, swaybrace appendages on suspension equipment, vortex generating devices, and antennae can impact results significantly. The model scale clearly has an impact in store balance selection. Small scale stores may preclude full six-component balance installation and often four or five component balances are used instead (usually excluding roll moment and or axial force). Consequently, to provide fully accurate coefficient information, the missing data must be supplied from external sources. The difficulties encountered at small scale can be offset by testing the store in freestream at the largest scale possible. Interference aerodynamics are obtained from the flowfield determined coefficients by subtracting the freestream aerodynamics for the same small scale store at the same attitude. Consequently, the effects of loss of model details are removed from the interference aerodynamics.

4.1.3 Analogy Methods

Clearance of a store can often approached from an analogy standpoint; that is, when similarly shaped stores that have been previously flight tested and for which the preponderence of data show that from similarity the new store can be tested in a low risk manner. In these instances, a number of store characteristics are compared between the two stores - the new store and the store that has already been tested - and a conservative buildup flight test program is accomplished. The analogy is established on the basis of mass and physical similarity between the two stores including the planform areas. Freestream aerodynamic data is generally compared between the stores and if experimental data is not available, aerodynamic estimation codes are used to generate a comparison. Since the missing data is normally the interference flowfield effects, in attempting to establish the analogy, one should consider differences in where the two stores are positioned in the flowfield. This is to say that the location of each store's lifting surfaces at various locations in the flowfield should be noted as well as the similarity in the store suspension system. A primary consideration is any variation of store center of gravity relative to the ejection force. Imparted ejection moments should compare favorably both in magnitude and direction. Six degree of freedom simulations without flowfield data can be executed with important aerodynamic coefficients varied parametrically - but caution should be exercised in evaluating the results. Using the approach successfully is predicated on sound, well documented historical data in the form of flight test reports. The propagation of analogies based on other analogies should be avoided. It is best to base each analogy clearly upon well documented, hard test results and data. Obviously, the basic advantages this method offers is a minimal cost program for generating a flight clearance by circumventing the cost and lead time required for wind tunnel testing. The technique is best suited to minor design changes for previously cleared stores, or for stores of similar shapes. For an agency like the OAC that processes over a hundred flight clearances each year, the use of analogy techniques have proven an effective approach when properly applied. The greatest disadvantage is in the relative risk, the relative increase in flight testing, and the amount of judgment and experience that must be relied upon in deciding upon the approach for a particular problem.

4.2 Specific Techniques Used by the NATO Nations

In order to determine what techniques were being used in the nations outside the US, the authors visited several government and industry organizations in other NATO nations and found that, in essence, all the techniques used in the US are being used by other countries; at least to some degree. Some real innovative application of proven techniques were uncovered, such as the method of actually measuring captive store loads during flight testing and then using data to perform six degree of freedom trajectory calculations (Netherlands), and the development of an Accelerated Model Rig (AMR) for accurate freedrop wind tunnel testing (United Kingdom). The authors found that the well documented wind tunnel techniques such as grid survey and freedrop are being used; however, not as extensively as theoretical methods. In the US the reverse is true (at least presently). That is, in the US the wind tunnel based methods are extensively used. The reasons for the difference in emphasis between theoretical and wind tunnel methods will be discussed in subsequent paragraphs.

At this point it is useful to outline the techniques and methods used by several of the NATO nations and the reasons why they selected the particular technique. The purpose of this section is to serve as a basis for stimulating engineers and managers in various government and industry organizations to use the AGARD channel to submit and dissiminate additional information on internal capabilities, techniques, and procedures for use by the aircraft/stores compatibility community. The authors stress this because of their inability to obtain anything more than an overview of capabilities during their short visit to selected organizations.

4.2.1 United States Air Force (US)

The OAC has established informal guidelines in deciding what techniques are best suited to a particular store separation problem. Generally, since most stores are carried in complex configurations, and released from multiple carriage racks at transonic speeds, experimentally determined flowfields is the preferred methodology. In fact, before proceeding any further, it may be stated, based on a review of OAC records over the last several years, that wind tunnel based prediction techniques have been used in the following proportions: CTS - 15%, grid - 70%, flow angularity - 10% and freedrop - 5%. The authors informally polled AEDC personnel and were told that CTS was used 50% of the time, grid and flow angularity was used 35% of the time and freedrop was used 15% of the time. These percentages give a good indication as to the degree the various techniques are used by industry and government throughout the US.

By using the experimentally derived flowfield approach, a general flowfield data base is continually expanded to include additional stores and aircraft. The OAC has developed an extensive data base for the F-15 and F-16 aircraft. Data exists in both grid and flow angularity format. As a cost savings measure, the grid is normally acquired in the "limited grid" mode described in an earlier section. During each test, however, the limited grid is compared with selected full CTS trajectories to verify the grid data base. For stores of large planform area, the store grid is acquired both as a function of vertical distance from the captive position and the pitch attitude of the store. Generally, freestream data for each store is acquired at the same scale as the flowfield grid, but for stores with complex shapes, larger scale data is acquired if at all possible. The consideration here is primarily the availability of funds to cover the cost of wind tunnel testing. Stores such as bomb racks and fuel tanks that have a pivoting release mechanism cannot be practically tested using CTS. Only for these type situations is the freedrop method used. When freedrop testing is performed, heavy scaling is used.

Analytical methods are currently restricted to single carriage stores at speeds outside the transonic flow region (Mach number less than 0.9 and greater than 1.1) For this reason, analytical methods are not routinely used. Analogy methods are used extensively. Analogy methods are supported by an extensive flight test data based and computer simulations using appropriate data when necessary. Every available source of information is cross-referenced when exact aerodynamic data is not available.

The six degree of freedom computer program is the mechanism used to actually calculate store separation trajectories. The program used by the OAC is fully documented in Reference (29) and (30). The program uses a look-up format for all required input data such as ejection force, flowfield, store mass properties, aircraft flight conditions and so forth. The program is an adaptation of the DI-MODS modular trajectory simulation developed by Litton Systems. It has been extensively modified to suit the special purposes of the OAC. For example, the program can be used to address maneuvering release of stores with post aircraft maneuvering. Output from the program is in a multifaceted digital format. However, computer generated plots are the primary means for analyzing store separation trajectories. The computer graphics program is fully described in Reference (31). Incidentally, computer graphics portrayal of store separation trajectories provides the store separation engineer with a valuable analysis tool. The engineer is able to quickly "see" the trajectory instead of having to analyze "mundane" data plots. Practically every organization is now using computer graphics in some form or the other. The rapidly expanding field of computer graphics offers ever new opportunities for enhanced analysis. Figure 16 is an example of enhanced computer graphics where the store and aircraft can be viewed from any angle. In addition, physical clearance between any points can be displayed. The sensitivity of the trajectories to various parameters can be studied to determine trends and to formulate a flight test program to validate the predictions.

The OAC has a policy of documenting each store separation program in the form of what is called an "Aero Memo". Each memo contains background information, store characteristics, aerodynamic data used, similation results, and ends with a recommendation for a flight test program. Extracts from two of these memos are included in this report as Appendices A and B. The reader may gain additional insight in the actual-application of the techniques described in this section by understanding how two real world problems were approached. Memos such as these are never published as they are used as internal working documents only. Two memos are presented because they contain different, and commonly used approaches in the OAC. In Appendix A, HARM missile/rack jettison trajectories from the F-4 were predicted by performing grid wind tunnel testing with limited CTS trajectories to verify trajectories generated using the grid data. In Appendix B, CBU-89 store trajectories from the F-16 were predicted using an analogy-grid approach. Basically, available grid data for an analogous CBU-58 store were used in conjunction with the freestream data for the CBU-89 store. The interested reader is encouraged to consider the flight test program that he or she would have formulated based on the results of the predictions. As will be mentioned in some detail in the next section, the scope of the flight test program, at least in the US, is largely influenced by safety of flight, cost, and time factors.

A very real problem in store separation today is multiple bomb rack jettison. Associated with every employment envelope established for stores is a jettison envelope for the rack from which the stores are released if the rack itself is jettisonable. For example, MER-10 and TER-9 multiple bomb racks are jettisonable. Jettison of racks can be very dangerous. It would be very expensive to wind tunnel and/or flight test all possible combinations of rack/store configurations that could be encountered. For example, the normal release sequence for the six stores from a MER-10 alternates from aft to forward rack stations. If, for example, a malfunction occurs as stores are released, leaving three stores forward and two stores aft, one store forward and no stores aft, and so forth, and the pilot is now forced to jettison the rack with remaining stores, one can see that separation can be quite a problem due to the unusual aerodynamic arrangement and large off-center weight. Since racks are normally only jettisoned in an emergency there is little incentive to spend any more money and time than is necessary to establish a benign safe jettison envelope. Because bomb racks are very narrow, use of the CTS is generally precluded due to sting mounting incompatibilities. As a result, wind tunnel testing has, in the past, resorted to freedrop testing. Unfortunately, this approach does not satisfy the economic considerations when dealing with the scope of the problem. Consequently, a technique for establishing a more efficient return on generated data and allowing more flexibility in studying rack jettison questions was needed by the USAF. As a result, the OAC developed a technique called the

Multi-carriage Bomb Rack Jettison Computer Simulation Techniques (MST). The technique is documented in Reference (32). The technique offers a method for predicting the trajectories of bomb racks which are of low density, are aerodynamically unstable, and have wide center of gravity and moment of inertia variations. All of these characteristics contribute to coupled angular motions. Because of the complex nature of the problem, it can best be solved (in the authors' opinion) experimentally.

The MST acquires total flowfield aerodynamic coefficients from two sources. First, the rack with attached stores is mounted on an instrumented pylon (internal pylon balance) and aerodynamic data are obtained for the total installation in the captive carriage position. Next, freestream aerodynamic data for the rack/store configurations are obtained using a larger model scale to facilitate sting installation. Once this data is obtained, it can be subsequently used in support of this type of work on other aircraft. These data form the starting point for determining captive carriage interference aerodynamic coefficients. Interference coefficients are decayed exponentially with vertical distance with respect to the pylon. The resulting data is used in a six degree of freedom computer program, along with other necessary input data to obtain rack trajectories. The technique has been validated with freedrop tests for a variety of rack configurations and Mach numbers with very good correlation. This technique is very useful for subsonic flow, but does not agree as well for supersonic flows where more complex patterns of shock flow exist. Some a-priori knowledge of the flowfield is needed to establish decay constants through previous tests and extensive freestreem data is needed. This is the principle disadvantage to the technique. Yet, it does provide more data versatility than the freedrop method, and gathers installed loads data in the process which may be useful for later studies.

4.2.2 United Kingdom (UK)

During the visit to the UK, the authors visited with representatives from several agencies and organizations, all of whom are actively involved in store separation and each of which utilizes one or more techniques.

Aeroplane and Armament Experimental Establishment (A&AEE) Boscombe Down

Aircraft/store certification requirements emanate from the Royal Air Force (RAF) and are submitted to the Ministry of Defense/Procurement Executive (MOD/PE), who processes validated requirements to the A&AEE. A&AEE evaluates the requirement and assesses whether flight testing can be performed without the need for analyses or wind tunnel testing, or if flight testing can be dispensed with and the requirement met by analogy to an already certified aircraft/store configuration. Usually flight testing is required. In fact, even for analogy situations, flight testing is usually performed to demonstrate satisfactory store separation at the corners of the flight envelope. When analyses or wind tunnel testing is deemed necessary, A&AEE solicits assistance from aerospace firms or other government organizations through MOD/PE. Upon receipt of predicted store separation characteristics, A&AEE formulates the flight test plan and conducts the testing. The initial test point is selected on the basis of judgment and experience. Subsequent test points are based on results of predictions and actual results after each test mission. A&AEE utilizes externally mounted cine cameras to record store separation trajectories. Cine film is reduced using a photogrammetric data reduction program called ATRAJ. While this system has worked well in the past, A&AEE has taken the initiative to develop a video camera system. The system (the first of its kind seen by the authors) offers to revolutionize data gathering for compatibility testing and will be discussed in a subsequent section.

Royal Airplane Establishment (RAE), Bedford

RAE Bedford is not directly involved in aircraft/stores compatibility testing. In the authors view, RAE can be likened to the US's National Aeronautics and Space Administration (NASA). They have their projects and flight test resources. They perform basic research, concept evaluations, and system assessments (RAE Bedford developed the first Heads Up Display). RAE Bedford has taken a leadership role in the UK in developing theoretical prediction techniques for store separation. Techniques are then made available to industry and government in the UK.

RAE Bedford has developed a store prediction technique called RAENEAR (an improvement of the NEAR technique). This technique is a panel method and is valid for stores with circular cross sections. RAENEAR calculates the flow field, calculates store loads, and uses the equations of motion to calculate the trajectory. Advantages of RAENEAR are that it is cheap (does not require expensive wind tunnel testing) and quick; although the definition of "quick" is relative. At the present time, each run requires several hours of computer time. A disadvantage of RAENEAR is the limitations of aerodynamic theory (particularly in the transonic Mach regime and at high angles of attack) which impacts prediction accuracy. RAE Bedford acknowledges that theoretical methods are far from being reliable enough to dispense with wind tunnel techniques. However, they are convinced that with RAENEAR, critical configurations, speed regimes, areas of difficulties, and so forth, can be evaluated at less cost than by only performing expensive wind tunnel testing. RAENEAR is fully described in Reference (33) and an overview of RAE Bedford prediction methods is contained in Reference (34)

British Aerospace (BAe) Brough

BAe Brough uses both theoretical and wind tunnel techniques to predict store separation trajectories. Both RAENEAR and SPARV, Reference (35), theoretical techniques are used. BAe Brough is enhancing RAENEAR by improving its computational efficiency and accuracy, improving modeling and aerodynamics, and extending its applicability to non-circular ejected stores, Reference (36). SPARV is a panel program which calculates store forces and moments at any position in the trajectory and then uses a Runge Kutta iteration to predict the movement of the store. BAe Brough states that the method is still in its infancy and will be improved by incorporating semi-empirical techniques such as cross-flow drag and viscous effects. They feel that SPARV is better than the simpler RAENEAR because of the greater potential for extension as modeling techniques for panel methods improve. SPARV is applicable to complex geometries and, hence, can easily handle effects of geometry changes. The SPARV program has been validated to some degree by comparing predictions with flight test results. BAE Brough states that a shortage of high quality flight test data has been a major stumbling block in investigating the relative merits of various prediction techniques.

Turning to their wind tunnel capabilities, BAe Brough operates a blow-down tunnel with a 0.68 square meter test section. The relatively small size of the tunnel dictates use of small models on the order of 1/30 scale (they have 1/28.5 scale Hawk aircraft, 1/30 Buccanner and Harrier aircraft, and 1/30 scale Tornado aircraft). Because of small tunnel size, the freedrop technique is preferred and its use has been optimized for their blow down tunnel.

BAe Brough has evaluated the pros and cons of the various scaling methods and selected light model scaling. To compensate for the gravitational deficiency associated with this scaling method, a unique Accelerated Model Rig (AMR) was developed. The function of the AMR is to accelerate the model of the aircraft upwards during store separation. Using a 1/30 scale model, the AMR accelerates the aircraft upward 29g during store separation. This 29g coupled with the 1g natural gravity field approximates that which would occur in an ideal 30g field. The upward acceleration of the model can be maintained for about 20 milliseconds (an additional 20 milliseconds is allowed for deceleration to rest) which equates to 0.6 seconds full scale. This is adequate for most stores to leave the near field of the aircraft. Correction of the gravitational deficiency using the AMR accounts for the largest (first order) error associated with light model scaling. The other source of error is the induced incidence of the aircraft as a result of its upward acceleration, and the induced incidence of the store as a result of the gravitational deficiency. To minimize errors from this source, BAe Brough has devised the technique of adjusting the pitch rate of the ejector. The validity of the AMR has been established by virtue of good comparison of predicted/actual store trajectory results. Data comparisons are presented in Reference (37) along with a detailed discussion of the AMR design and construction details.

Although BAe Brough has a viable AMR system, several improvements are planned. For example, the ejection force simulation will be improved and end of stroke velocities will be measured using a laser doppler technique. Trajectory analyses will be enhanced by implementing a data reduction system that is similar to the US's Graphic Attitude Display System (GADS) used for cine camera film reduction GADS will be discussed in a subsequent section. Use of this type of data reduction system in a wind tunnel application would be entirely new. It may be noted that at the present time, cine film is reduced using either a one or two camera solution. BAe Brough is looking into ways of changing the aircraft incidence during aircraft acceleration (perhaps with a microprocessor controlling the parent aircraft rack and pinion system). This would eliminate the need for adjusting the ejection force/moment. Lastly, they are evaluating increasing the maximum wind tunnel operating stagnation pressure from 4 to 9 atmospheres. This would have the effect of increasing Reynolds Number (RN) to 1/4 to 1/5 of full scale values. A final thought on the AMR system. It may be noted that the system can only be used for single store releases due to the short time available for accelerating the parent aircraft model. However, this has not proved to be a serious limitation for BAe Brough since most of the releases that they are required to support are single releases.

BAe Brough also operates two other wind tunnels in support of store separation testing. The Open Jet Wind Tunnel (2x2 foot test section) is used for free drop testing. Light model scaling without gravitational correction is used. For 1/7 scale (typical) the acknowledged trajectory error is about one meter vertically at 0.5 seconds with an induced incidence error of about one degree at Mach 0.5. Multiple store releases are made in this tunnel. Use of heavy model scaling was considered, and rejected, because of the need to increase store density to high values that required models to be constructed from exotic (and expensive) materials, and the need for high ejection forces.

The BAe Brough Low Speed Wind Tunnel is a continuous flow tunnel with a seven by five foot test section (velocities up to 250 ft/sec). Freedrop testing in this tunnel uses Froude scaling due to low Mach requirements. Normal model scales range from 1/10 to 1/12. Testing in this tunnel is primarily devoted to evaluating emergency jettison of stores during take-off and landing conditions. The reader is encouraged to read Reference (38) which describes in some detail the store separation methods used in the UK. Intuition, RAENEAR, light model testing, and the AMR are all discussed in this reference.

Aircraft Research Association (ARA)

ARA is an independent cooperative research and development organization set up in 1952 by 14 UK aerospace firms. It is non-profit and is not government owned. ARA operates two continuous and four intermittent wind tunnels. The focal point of store separation activities is the 9 by 8 foot transonic wind tunnel (up to Mach 1.4). ARA utilizes freedrop testing using light model scaling (with a simple vertical displacement correction factor incorporated into final reduced output data to account for the gravitational deficiency).

ARA operates a Two Sting Rig (TSR) which is similar to the US's CTS. Figure 17 shows the general arrangement of the TSR with a Tornado aircraft model installed. The TSR is described in Reference (39). The TSR is used in either the trajectory or the grid mode. This system was validated in 1978 by comparison with flight test data and a US CTS. The TSR can be used up to Mach one. Typical model scale is 1/10. Position accuracy is advertised as plus/minus 0.05 inches and 0.15 degrees.

ARA is very active in theoretical prediction methods. They believe that these methods are needed to complement wind tunnel work. ARA has used the Nielsen method (Reference (40)) and validated it to high subsonic Mach. The method is used to support wind tunnel studies before actually conducting testing. ARA is convinced that in the future there will be an ever increasing use of theoretical methods to complement wind tunnel testing. Incidentally, ARA used the Nielsen method to optimize lateral spacing of stores on a Twin Store Carrier (TSC). Because of these studies, subsequent wind tunnel testing was much reduced in scope had studies not been performed. The reader is encouraged to read Reference (41) which fully describes store separation testing at ARA. ARA's opinion as to the advantages and disadvantages of mathematical modeling, TSR, and freedrop are all discussed in this reference.

4.2.3 Netherlands (NL)

The authors visited the National Aerospace Laboratory (NLR) which is a government subsidized organization. NLR has extensive store separation prediction and test capabilities for aircraft used by the Royal Netherlands Air Force (RNLAF). They have a complete NF-5 and F-16 capability. NLR is the recognized authority on compatibility matters in the Netherlands, and accordingly, the RNLAF relies on NLR for technical expertise. Basically, the RNLAF provides NLR with their certification requirements and NLR then performs compatibility analyses, and formulates and orchestrates flight testing which is performed by the NRLAF.

NLR can predict store trajectories using theoretical, grid, flow angularity and freedrop methods. When wind tunnel testing is required, NLR prefers use of the grid method. This is because, as mentioned in an earlier section, grid data can be used off-line to perform trajectory analyses. Trajectories are calculated using a six degree of freedom computer program called VORSEP. VORSEP accepts aerodynamic parameters as inputs. The model can be operated in two ways: (1) to predict store trajectories when aerodynamic coefficients are obtained from theoretical studies, wind tunnel tests, or from tests with the NLR full scale captive store load measuring system (described in subsequent paragraphs), and (2) to determine aerodynamic coefficients from store trajectory data measured in a wind tunnel or from full scale store separation tests. In these cases, the model initially uses predicted coefficients to produce a predicted trajectory and the coefficients are adjusted until the predicted and actual trajectories coincide. VORSEP, the NLR panel method, and other prediction techniques used by NRL are fully described in References (42) and (43).

In addition to the above, NLR has developed, and validated, a unique, full scale flight test captive store load measuring system. This system consists of a support structure suspended from a bomb rack, a five component load measuring balance, and a replaceable store shape (which is made as light as possible to minimize inertial forces). The system is designed so that in-flight airloads may be measured with the store in a captive carriage position and in a displaced position (with a spacer placed between the store and the carriage rack). Figure 18 shows an NF-5 test aircraft with a fuel tank mounted on the captive store load measuring system in the displaced position. This is a well instrumented aircraft for store separation testing. The instrumentation is described in Reference (44). The basis for selection of this nominal offset value was NLR studies which show that interference aerodynamic forces decay rapidly to small values by the time one store diameter is reached. This correlates with USAF results. The system has been validated on the NF-5 using a number of low density store shapes such as the BLU-1. NLR experience is that store separation trajectories based on flight test full scale captive loads are far more accurate than theoretical or wind tunnel based predictions. Incidentally, NLR believes that this system is particularly suited for their use since the NF-5 carries stores on parent pylon and on multiple carriage racks and many stores are of the low density, unguided, variety. The NLR captive store loads measuring system is fully described in Reference (45). As a follow-on activity, NLR is developing a self-contained instrumentation package that will allow tests on normal operational aircraft. The present system must be used on a specially instrumented aircraft since data is recorded on the aircraft.

When a new certification requirement is received by NLR, an assessment is made to determine if the store can be certified by analogy. NLR acquired an extensive aerodynamic data based for stores certified on the NF-5 by the airframe contractor. This data base is very important to NLR and serves as a basis for analogy type certifications. If a new store fits within the analogy criteria, no further analyses are performed and flight testing may or may not be conducted. If an analogy does not exist, store trajectories are initially predicted using the NLR panel method. Results are used to identify safe, marginal, and unsafe areas of the flight envelope. If results show safe separation throughout the flight envelope, no further analyses are necessary and flight testing is conducted only as necessary to validate predictions. If results show marginal or unsafe areas of the flight envelope, NLR may request that the RNLAF first perform flight testing using the captive loads system. NLR reports that three missions are usually required to gather store airloads data for each configuration (one mission with the store in the captive carriage position and two missions with the store in displaced position). Store airloads are subsequently used in six degree of freedom computer program to predict store separation trajectories. NLR reports excellent agreement between predictions and actual results. In fact, data contained in Reference (46) show that for LAU-3 and BLU-1 stores, trajectories predicted using the captive load system compared very well with actual results. On the other hand, predictions based on the NLR panel method and wind tunnel data did not compare nearly as well (particularly in the pitch plane). In view of proven results, NLR naturally attaches high confidence to predictions using the captive store loads measuring system. This system has enabled store separation flight testing to be performed with lower risk and fewer missions than would otherwise have been possible. It may be noted that NLR starts flight testing at a point judged to be very safe (based on experience). If there are any significant differences between predicted and actual results, carriage loads are extracted from actual results and used to update predictions. This process is continued until separation envelope goals have been achieved.

Before closing this section it should also be noted that NLR has developed their own data reduction program, called MILLIKAN, to support store separation flight testing. The program converts store images on movie film to six degree of freedom digital data. This program uses a single camera solution. The MILLIKAN system is fully described in Reference (47).

4.2.4 Canada (CA)

The development of a Canadian Forces (CF) store separation prediction and test capability has been rather recent. Yet, the CF has already developed a baseline capability along with plans for further growth. Historically, the CF certified stores on their aircraft by analogy to stores certified on another country's aircraft or by performing flight tests. The problem with the analogy method was that the CF frequently found that another country's flight envelopes were too restrictive for their use. As no pre-flight prediction techniques existed, the CF resorted to brute force flight testing. The CF found that this type of testing was too expensive, too time consuming, and too resource expensive for their purposes.

The above operating procedure might have remained unchanged were it not for the decision to enhance the CF-5 external stores capability. The CF-5 program provided the opportunity for the CF to develop and acquire a prediction and test capability. The CF (through DFTEM 4-4, CF office of primary responsibility for stores compatibility) were aware of, and liked, the manner in which stores were being certified by the RNLAF on the NF-5 with the assistance of NLR. This stimulated the CF to establish an in-house prediction and test capability utilizing Canadian industry (Canadair LTD) in conjunction with the government's National Aeronautical Establishment (NAE) High Speed Aerodynamics Laboratory, and the Aircraft Engineering Test Establishment (AETE). Initially, the CF established a joint Canadair/NLR effort to certify the SUU-25 and BL-755 stores on the CF-5. During this program Canadair obtained NLR prediction methodology and AETE developed instrumentation and test techniques.

The first in-house application occurred in 1978 when the CF was tasked to certify the LAU-5003 rocket launcher (with various weight warheads) on the CF-5. Canadair performed preliminary trajectory analyses using their store separation model to determine critical configurations and to form a basis for establishing a flight test plan. During AETE flight testing (using an instrumented captive airloads measuring system like that used by NLR) actual results were compared with predictions and, where necessary, predictions were upgraded before proceeding to the next test point. Following successful completion of the program, LAU-3 and LAU-5002 rocket launchers, AIM-9 missiles, and an airborne instrumentation pod were certified by purely analytical means saving the CF substantial funds, time, and resources.

The Canadair store separation model is described in Reference (48). This program is written in Fortran specifically for use on Canadian computing facilities. Basically, it is a modular six degree of freedom program so that it can be used to support any compatibility program (its use is limited to unpowered axi-symmetric stores). It consists of a MAIN program which utilizes store and aircraft mass and geometric input data an calculates and tabulates the actual trajectory. Subroutines consist of ATMOS which processes altitude and velocity parameters, LIFT which processes store and aircraft aerodynamic parameters as a function of flight condition, EJECT which converts ejection forces into store forces and moments, AERO which calculates total (freestream plus interference, or freestream plus captive) store aerodynamic loads during the trajectory, and PLOT which plots the trajectory. In LIFT the aircraft angle of attack remains constant during store separation; in EJECT ejection force "recoil" is included. Forces are varied from pylon to pylon in AERO, captive store loads are decayed to freestream by the cube of the aircraft wing aerodynamic chord. In addition, the simplifying assumption is made that store freestream and interference forces can be treated independently. Accurate inputs to AERO are obviously the key to accurate trajectories. AERO can accept experimental, theoretically derived, or captive store airloads measured with an instrumented store (this has been done successfully at AETE).

In the theoretical area, the NAE initiated a multi-faceted effort to develop and purchase computer prediction codes and to acquire and fabricate wind tunnel equipment to support store separation programs. Several codes are in use and development to generate store freestream aerodynamic forces. The Jorgesen code is used to predict forces and moments on slender bodies up to 180 degrees alpha (subsonic and supersonic). This code is based on slender body and cross flow theory and has been extended for use up to Mach three; a code termed AKCAX is being developed to predict the freestream pressure distribution and drag for slender bodies at zero degree alpha and to predict side force at high alpha. The Mendellhall code is used to predict freestream forces and moments on wing/body/tail store configurations up to 35 degrees (subsonic and supersonic). This code is based on lifting surface theory which utilizes vortices shedding from the body nose and the wing edges. Plans are to acquire a cross-flow code to be able to predict freestream forces and moments (subsonic and supersonic) up to high alpha. Interference forces and moments on a store as it translates through the aircraft's flowfield are predicted subsonically using the three dimension NLR panel method and transonically using the equivalence rule/cross flow developed by NAE and solved by the NLR panel method. This method is characterized by short computer times. The Dillenius code is used to predict store captive loads. RAENEAR (valid for stores with circular cross sections) and NEAR (not limited to circular cross sections) prediction programs are also in use. Present plans are to compare predictions with flight test data to assess prediction accuracy.

It is clear from the above that the CF has developed, and is enhancing, their prediction capabilities to support current and future efforts such as for the CF-18 aircraft/stores compatibility program. Current plans are for a contractor to perform trajectory predictions and provide flight test support for initial baseline store configurations. This will establish a data base for the CF, and put the CF in a posture to perform follow on certification efforts totally in-house begining in 1986. Along these lines, the CF is already planning on obtaining their own 6% CF-18 wind tunnel model. The reader is encouraged to read References (49) to (53) which describes in considerable detail Canadian store separation methodologies and capabilities.

4.2.5 France (FR)

During their short visit to France, the authors visited Avions Marcel Dassault-Breguet (St. Cloud). Dassault has extensive prediction capabilities utilizing both wind tunnel based grid, freedrop (using light model scaling), Captive Trajectory System (CTS) methods, and theoretical methods. Because of the wind tunnel's high cost, and the ability to perform parametric studies and pre-flight comparative analyses, theoretical methods are preferred.

The aircraft flow field is theoretically predicted: subsonically, using the singularities method with a distribution of sources, sinks, and vortices on the aircraft surfaces and divided into a large number of elements (this method requires high computing time); and supersonically, using the finite difference method (which assumes isentropic flow and does not consider shocks).

When wind tunnel testing is performed, the French industrial wind tunnels are used. A configuration analysis is performed to determine which test techniques should be utilized. For example, is the store stable or unstable, low or high density, located adjacent to another store, high or low wing/tail aircraft configuration, speed regime, and so forth? Subsequently, the physical and mechanical limitations of the wind tunnel and limitations associated with the test technique itself are evaluated, and based on results, a test technique (grid, CTS or freedrop) is selected.

A recent application of in-house capabilities has been in support of the Mirage F-1 program. Store separation wind tunnel testing, using 1/15 scale models, was performed. Dassault reported large yaw differences between predicted and actual results. In the wind tunnel, the missile nose yawed inboard whereas in flight, the missile did not yaw at all. This was surprising to the authors, but new, as similar anomalies were noted by the Air Force during wind tunnel testing performed in suppor the A-7D flight test program.

4.2.6 Germany (GE)

The authors visited Dornier at Friedrichsafen and MBB at Ottobrunn during their short v to Germany. These firms perform compatibility analyses and testing under contract to the German government. For aircraft in the development phase, the German procurement office contracts for the aircraft and this contract includes the stores the aircraft must carry and release (baseline store During the development phase, firms normally perform extensive wind tunnel testing to optimize the e of the aircraft to ensure successful integration of baseline stores. These test results are revi y the German government representative (military certification agency BWB-ML). On the basis of the est results, BWB-ML issues a preliminary flight test authorization as necessary to conduct the next mission. Without a clearance from BWB-ML the firm is not allowed to fly. If a new certification requirement is validated for an existing (inventory) aircraft, BWB-ML decides whether the German government test center will, or can, handle the task alone. Normally, if there is no need to modify the aircraft, BWB-ML decides that the German test center will perform the test. In this event, the test center engineers write a proposed test plan and discuss the test plan with BWB-ML. If BWB-ML concurs, they issue a flight authorization to the test center to allow testing to start. Again, after each mission, BWB-ML reviews results and, upon program completion, issues the final certification which allows the German Air Force to fly within the certified envelope.

Two examples may serve to illustrate the operating relationship of BWB-ML with respect to the firms. In the first case, there was a requirement to establish an Alpha Jet emergency jettison envelope for a twin store carrier loaded with stores. The contractor recommended that wind tunnel testing be performed before initiating flight testing. BWB-ML determined that flight testing could be initiated without wind tunnel testing, and this is in fact what was done. In another example, for a major new missile certification effort on the F-4, MBB predicted missile separation characteristics. BWB-ML then reviewed these calculations and issued a flight clearance to the German test center. After each mission, results were used to upgrade the calculations for the following mission. In this example, BWB-ML made the determination that a joint firm/government participative program was in the best interest of Germany.

MBB: MBB uses SSP (Store Separation Program) code which relies on flow fields, captive loads, free flight aerodynamics and ERU-characteristics, all determined either by theory or by experiments. In development since 1974, this code has been used to evaluate most clearances needed for the Tornado fighter aircraft where it has been used to optimize the minimum release intervals for multiple bomb releases. For retarded bombs, the intervals were nearly halved by this theoretical optimization and successfully flight tested within the operation envelope. The MBB-SPP has recently supported multi-firings of the Tornado/MW-1 ammunition. References 54-56 present an excellent discussion of the MBB-SSP methodologies.

Dornier: Dornier employs a variety of prediction techniques such as grid, free drop, and theoretical. Theoretical techniques and free drop appear to be the centerpiece of Dornier's methodology. Although a store data base is maintained, theoretical store separation predictions are always made, even if a new store is analogous to a certified store. Dornier has had good success using theoretical methods and free drop which are documented in References (57) and (58). An interesting application described to the authors was in support of a tow target system. Problems were being encountered during target tow. The system was modeled mathematically and parametric studies were performed which identified a fix. The fix was implemented, tested, and proved successful during subsequent flight tests.

High confidence is placed on the accuracy of predictions using wind tunnel methods. However, wind tunnel testing is rarely used due to high cost. In fact, it is the authors' understanding that the wind tunnel is used only when there is an order for a production aircraft to support the high cost of testing. If wind tunnel testing is performed, free drop and grid (particularly for missiles) methods are used. Dornier examined use of light, heavy, and Froude scaling. Heavy model scaling is preferred although light model scaling is used for low density unstable stores. Judgement is used in selecting the best scaling method for the applicable task at hand.

5.0 STRUCTURING A FLIGHT TEST PROGRAM BASED ON PREDICTIONS

This chapter is one of the more important in this report. This section describes an approach toward structuring a separation program based on predictions in conjunction with safety criteria that are not documented elsewhere. Although this approach may not be accepted by others as the best one for every situation, it has been successfully used for the last 18 years by the USAF, and it is felt that readers should seriously consider its adoption.

5.1 Safety of Flight Criteria for the Test Program

With rare exceptions, flight testing should be performed in such a manner as to minimize, but not necessarily eliminate, the potential for aircraft-to-store contact during store separation. The flight test program (mission summaries) should be structured so that if a store should contact the aircraft, the contact will only result in superficial damage that would not affect safety of flight. Such store-to-aircraft contacts are categorized as "low risk". For example, a store that separates with a greater than predicted nose-down pitching motion might cause some store tail-to-aircraft pylon contact. The possibility of such contact should be accepted if nothing more than scratches are anticipated. If the goal were to entirely eliminate the possibility of any contact, the number of missions would have to be drastically increased to allow for minimal changes in aircraft release conditions between missions. This would result in significantly increased test cost and test time. While the need to minimize cost is as important in the USAF as it probably is in other nations, the authors have to say that it has been their experience that the need to complete the test in a timely manner frequently tends to override the cost aspect. Accordingly, the USAF has been motivated to performing testing in the most expeditious manner possible so long as the "low risk" approach is not compromised. To elaborate on the foregoing discussion, consider Figure 19. In a very simplisitic fashion, this figure conveys the view that if one wanted to absolutely minimize risk, one would have to conduct a large number of missions. On The other hand, if one were willing to accept a high risk, then one might not need to conduct any missions at all! That is, a store separation envelope could be established on the basis of predictions, analogy to a certified store, or just engineering judgment. Depending on one's record in predicting store separation characteristics using analyses, analogy, or engineering judgment, the actual risk might not be as high as one might suspect. For USAF purposes, two other parameters that were mentioned earlier - cost and time - are considered of major importance.

Just about every program with which the authors are familar was expected to be completed in the shortest time possible. Many programs were due to be completed "yesterday". That is, upon receipt of program go-ahead, the operational user was already asking why the enhanced capability that the program was to produce had not yet been received! This theme was mentioned in Section 4 from the standpoint of why a specific separation prediction technique was selected. The point also holds true when it comes to flight testing. It is obvious that more missions require more time, and time is something that is usually in short supply. Similarly, more missions cost more money and unless the program is of the highest priority, cost must be kept as low as possible because of prevailing budget constraints.

If one considers cost, time, and risk as interrelated, what the authors call a "performance factor" may be derived. If this factor is plotted as a function of the number of missions, it is apparent that there is an optimum number of missions that yields the highest performance factor as shown in Figure 20. This figure shows that there is an optimum number of missions for given conditions of cost, time, and risk. To the left of the optimum number of missions there is a rapid decrease in the performance factor. This is due to the fact that risk increases dramatically and dominates as the number of missions decreases. On the other hand, to the right of the optimum number of missions there is a more gradual decrease in the performance factor. This is because as more missions are added, cost increases dominate the combination of the two.

One should always strive to achieve the optimum performance factor for each program. But, how is this done? Unfortunately, there is no universal answer. Each country has its own "risk acceptance" or safety of flight criteria. In addition, each military service and each test organization usually has its own safety of flight criteria. For example, one test organization may view an occassional store-to-aircraft contact which may cause minor damage to the aircraft and/or store, but not jeopardize the flight safety of the aircraft and/or pilot, as routine and acceptable. Another test organization may view any contact as serious and unacceptable. Clearly, in the first instance the engineering community would structure the test program far differently from the latter case - in which more safety-enhancing build-up missions would be included. As for the time factor, the mission rate is highly dependent on an array of variables. For example, test support requirements, aircraft complexity (turn around time), store complexity (guided store or iron bomb), data reduction requirements and processing time must be considered. Similarly, each of these factors impact cost. Too many times engineers, in a building remote from the test organization, plan the test program oblivious to such factors as risk, cost, and time. A basic key to structuring the separation program is to build these parameters in from the outset.

With the aforementioned discussion as background material, the constraints used to meet "low risk" safety of flight criteria will be discussed. Basically, there are two primary constraints:

(1) No part of the store shall come closer to any part of the aircraft structure, suspension hardware, and/or adjacent stores, then it was during captive carriage.

(2) Upon release, the store shall separate with a nose-down pitch rate and a positive acceleration away from the carriage rack until completely clear of the aircraft flowfield.

Figure 21 illustrates the first constraint. Store A is in the captive carriage position. Store B is shown with its fins having translated above the captive carriage position due to a large nose-down pitching motion. This case is unsatisfactory even though, due to some lateral movement, it might miss the pylon. Store C is shown with its fins having displaced below the captive carriage position during separation. This case is what is strived for, and is satisfactory. Although we are discussing store motion only in the pitch plane, the same holds true in the other planes.

As far as the second constraint is concerned, a nose-down pitch rate and acceleration away from the aircraft are the primary keys to safe separation. They are also the most difficult constraints to achieve. Store D in Figure 21 is shown with a nose-up pitch attitude. While this store may have separated safely to this point, with a nose-up pitch attitude it could generate enough lift (depending on its aerodynamic characteristics, weight, and release conditions) to "fly" back into the aircraft. If one recalls Figure 3 where the F-111 fuel tank was released, positive downward acceleration initially existed but not for a long enough period of time for the tank to clear the entire aircraft flowfield as evident by the fact that it "flew" up and into the aircraft. Clearly, positive acceleration will always be present if the store separates with a nose-down pitching motion and maintains a nose-down pitch attitude until clear of the aircraft. This is why one should almost always select ejector rack pitch control settings to impart an initial nose-down pitching rate to the store. If the ejector rack only has one ejector piston and this piston is behind the center of gravity of the store one has no choice but to proceed with the test - very carefully. In this instance, the store separation envelope that can eventually be cleared is usually restricted because the initial pitch control needed to start the store with the desired angular motion is not present. One last point on the importance of positive acceleration during store separation. The USAF requires almost all stores to be released in a variety of flight conditions, including very steep dive angles. In a sixty degree dive (which is common) the initial acceleration due to gravity acting on the aircraft and the store in the plane perpendicular to the aircraft flight path is only +0.5 g. The authors have encountered instances time and time again where, at high speeds, stores separate with favorable initial nose-down pitching motions and then, shortly after release, pitch nose-up due to aircraft flowfield effects resulting in the relative acceleration between the aircraft and the store becoming negative in very short order. The store "flies", and hits the aircraft. The moral here is that one must be especially careful releasing stores in steep dive angle bunt maneuvers or climb angles (loft maneuvers where the aircraft is pulled into a steep climb and the aircraft load factor is reduced just prior to release) where the relative acceleration between the aircraft and the store is reduced below +1.0 g at release.

As the store separates it usually has to clear adjacent stores and/or aircraft structure to its sides. In general, no part of the store should come closer than one inch to adjacent stores/structure during separation. Figure 22 shows a typical aircraft/stores arrangement where the store has to clear adjacent stores during release. The figure shows a typical collision boundary for the store to be separated. Note that the collision boundary is violated if the store fins translate above the initial captive carriage position and if the store yaws to such an extent as to allow its fins to come any closer than one inch to adjacent mounted captive stores.

5.2 Methods for Structuring Flight Test Program Based on Predictions

Establishing aircraft/store collision boundaries is the first step in structuring a flight test program based on predictions. In the simplest example, a collision boundary is established as shown in Figure 23. An accurate (scale) drawing is prepared of the store in the captive carriage position on the aircraft (including any adjacent stores). Then the store is redrawn with its center of gravity displaced vertically a given distance (usually every six inches for the first several feet and then every foot up to at least one store length). At each vertical displacement, the store is rotated nose-down and nose-up in separate drawings until any part of the store intersects the captive carriage constraint (no part of the store shall come closer to the aircraft than during captive carriage). This procedure is repeated until the store can be freely rotated without contacting any structure. Generally, the store is drawn on a transparency and superimposed on the aircraft drawing at the various vertical locations to save time. As an example, Figure 23 shows the maximum nose-down pitch that can be sustained by a store without the store penetrating the captive carriage constraint. This constraint is a key ingredient to the go/no-go decision between flight test build-up missions and will be discussed shortly.

Before leaving the subject of collision boundaries, the reader will probably have already realized that cases where stores separate with purely vertical motion - without any lateral motion - and pure pitching motion-without any yawing and/or rolling motion is rare. In the above collision boundary example, this is of course what was assumed for illustrative purposes. Combinations of linear and angular motions during store separation obviously impact the collision boundary. One can calculate the collision boundary for any array of combinations of store pitch, yaw, roll, and vertical and lateral displacements. If this is done, hopefully it is done on a computer because it would be very time consuming manually. The authors have not found it necessary to do this at all. Actually, store separation trajectory predictions are reviewed and, based on these predictions, the appropriate collision boundaries are generated. This avoids having to prepare collision boundaries for an array of store angular motions/positions that are not predicted. Of course, during the course of flight testing, if predictions prove to be in error, then the collision boundaries are recalculated to correspond to actual motions/positions.

Now it is time to integrate store separation predictions with the captive carriage constraint. The most common type of output for store trajectory predictions is store angular and store linear values as functions of time. Figure 24 shows a plot of predicted store vertical displacement and store pitch attitude (with respect to the initial captive carriage position) as a function of time for various airspeeds. To be of use with the earlier constructed captive carriage constraint it is necessary to transform these data into a plot of store pitch as a function of vertical displacement. This is, of course, easily done and results are shown in Figure 24. The next step is to cross-plot store pitch at specific vertical displacements as a function of airspeed. As mentioned earlier, vertical displacements of every six inches are used for the first several feet and then every foot thereafter. The results of this cross-plot taken from the data in Figure 24 are shown in Figure 25. The final step is to superimpose the captive carriage constraint, and this is also easily done and is shown in Figure 25.

Let us examine Figure 25 more closely. The increasing spacing between vertical displacement lines confirms that the store is separating with a positive acceleration away from the aircraft. Of course this can be, and is, more easily ascertained by simply examining a plot of vertical distance as a function of time. This plot shows that the maximum predicted release speed is 500 KCAS. If the store is released at a higher speed, the store tail will contact the pylon. If one had complete faith in this prediction, the store could be certified (that is published in the pilot's flight manual) without any testing. Regretfully, such complete faith in these matters is not justified and, therefore, some flight testing is almost always required. Accordingly, this discussion will continue with how to structure flight test missions.

In Figure 25 note that the predicted store pitching motion increases very gradually with increasing speed. In addition, store pitching motion is always nose-down so one can count on positive acceleration away from the aircraft (at least initially). There are no abrupt discontinuities with increasing speed. In such a situation, a very limited flight test program is usually required. As an initial example, assume that the maximum aircraft carriage speed is 600 KCAS. In this case, since the predicted collision boundary is 500 KCAS, there is no need to worry about exceeding the carriage envelope during the test program. In the authors' opinion, an initial release speed of 400 KCAS would be ideal. This speed is 100 KCAS below the predicted collision boundary giving substantial margin for error in the prediction. A lower speed would be even more conservative but is not deemed necessary in this particular benign case. If the actual test results match predictions, the next release point might logically be 450 KCAS. If at this point, actual test results match predictions, the authors, in general, extrapolate test results to 500 KCAS and clear this point by analysis. Although the actual test results match predictions, at 500 KCAS the store would separate satisfactorily but just barely clear the pylon. Because of concern for maximizing test safety, the authors would not choose to demonstrate this point. In fact the store would be certified to 475 KCAS to allow for a possible "overshoot" of the maximum release conditions on the part of the pilot. As mentioned in an earlier section, the magnitude of the overshoot margin depends on the release conditions (straight and level, or dive delivery - which requires a higher margin) and other related factors. What if the maximum aircraft carriage speed were 400 KCAS? In this case, an initial relèase speed of 375 KCAS could be used which is consistent with the aforementioned philosophy of not testing at "end point" conditions. Even though there is an ample speed margin from a separation standpoint, the exact captive carriage speed should not be tested for fear of inadvertently exceeding this speed during the release maneuver. Accordingly, one should test at a lower speed, the value of which again depends on the type of aircraft and release maneuver. In this later case, the situation exists where only one release mission is required to demonstrate the envelope in a highly safe manner. One last note on this particular example. In the authors' experience, the situation where the predicted collision boundary is at a higher speed than the captive carriage speed is in the minority. In short, most of the time, the aircraft must be slowed down to safely release stores. Suffice it to say that in a combat situation, pilots do not want to slow down.

Now let us consider the case where predicted nose-down store pitching motion quickly increases dramatically with increasing airspeed as shown in Figure 26. In this example, the collision boundary is still 500 KCAS. However, because of the steep slope of the displacement curves, a slight error in predictions could make a big difference in the collision boundary. According, more caution is called for. In this case, flight testing should be started more than 100 KCAS below the collision boundary. The authors would select an initial release speed of around 350 KCAS, before the start of the area where the non-linearity with speed begins. If actual test results matched predictions, the next test point would be 400 KCAS, just about on the edge of the speed discontinuity. Again, if actual test results match predictions, a speed increase of no more than 25 knots would be attempted with 25 knot speed increases on each mission thereafter until reaching 475 KCAS. If at this point stores were still separating successfully and actual test results still matched predictions, actual test results would be extrapolated to 500 KCAS, and this point would not be tested as discussed earlier.

The most difficult, and perhaps most treacherous, case has been saved for last. Figure 27 shows store pitch-up below a given speed (in this case 250 KCAS) and store pitch-down above this speed. This case is typical of an unfinned and/or an unstable store. At low speeds, and high angles of attack, such stores are prone to nose-up pitching-motions, and at high speed and low angles of attack, are prone to nose-down pitching motions. But, this is not a hard and fast rule, just a generality. Clearly, the local flowfield drives the separation motion. The authors have encountered several cases where the store separates at low speeds with a nose-up pitching motion and as speed is increased, nose-up pitching motion continues to increase to the point where the store generates enough lift so as to "fly" back into the aircraft. But, at least the pitching motion is in one direction at all speeds. In this case, one can anticipate increased nose-up motion and plan for it just as was discussed previously for nose-down pitch. The dual pitch-down and pitch-up motion creates a much more severe problem. Unless one knows "exactly" the neutral point, one can select an initial flight condition that could lose an aircraft. This is, in fact, what happened to the USAF in the late 60s. The pitch characteristics of a Multiple Ejector Rack released with asymmetrically loaded stores (to represent a rack malfunction mode) from an F-4 as a function of speed the same shape as shown in Figure 27. In this example, the rack was released at a speed just above the neutral point (by luck). The rack separated with a very gentle nose-down pitching motion. In short, a great separation! The next test point consisted of releasing the rack 25 knots slower. The store pitched violently nose-up, contacted the aircraft causing severe damage, the crew had to eject, and the aircraft was lost. On hindsight, this contractor conducted program should have been structured differently. In the first place, the aerodynamic characteristics of the asymmetrically loaded rack were estimated and not measured in the wind tunnel. Therefore, the predicted separation characterisitics were not at all accurate. Once the nose-down separation motion had been established, the next test point, in the authors' opinion, should have been at a higher speed, not a lower speed, so that at least the semblence of a "trend" could be established. At a 25 knot higher speed, the very steep slope of the displacement curve should have alerted the test engineers to the high probability that if this trend were extrapolated back to a lower speed, a severe nose-up pitching motion might be the result. Then, with this steep slope as a caution flag, only a very small speed decrease, if any, would have been in order. One should never proceed into an area of nose-up pitching motion unless one knows precisely the aerodynamic characteristics of the separating store, or unless the dynamic pressure is so low the store cannot possibly generate enough lift to rise. Failing this, one must make very small speed adjustments between missions if one proceeds in a brute force manner.

The preceeding method of using predictions plotted as a function of speed is clearly the authors' choice. However, there is another method used by a number of industry engineers which is quite different, and which will be discussed for the reader's consideration. In this method, a point in the center of the desired employment envelope is selected as a starting point for testing as shown in Figure 28. The store is released at this benign speed condition, at or near the maximum allowable load factor. For example, the store may be released at 350 KCAS in +6g symmetric pullup maneuver. Actual results are compared with predictions and if a good match is obtained, the same point is repeated but at a lower g, perhaps half the original value. The procedure is repeated until 1g is reached. Then, if a match is still obtained, a release at the minimum "g" is performed. This same procedure is then followed, expanding the envelope in all directions, until points on all corners of the employment envelope have been covered. The proponents of this method claim that less missions are required. This may be true, but the less straight forward way of expanding the envelope may be more of a disadvantage than any pure saving of missions. With the collision boundary method, one can more easily relate to the envelope as it is being "opened up". In the latter method, it is difficult to know just what envelope is achieved as testing proceeds because safe separation may occur throughout the desired envelope, but only at various "g" levels. Such an envelope would be of little value to flight crews. In effect, additional cross-plotting of data is required to arrive at a usable envelope for consistent "g" lev

In attempting to decide at which condition to begin flight testing so as to minimize risk, we have found a simple technique which is often useful. The lift of a body is equal to the of the store lift curve times the angle of attack of the store times the dynamic pressure times the reference area of the store. Now, one can set the lift equal to the store weight. The slope of th lift curve can be assumed high. The angle of attack of the store during separation can also be ass high. The reference area of the store should be known. With these values, one can solve the equa for dynamic pressure which can then be related to an equivalent airspeed V_e. This V_e is the one a which the store will most probably rise, or "fly", and endanger the aircraft. Below this airspeer is little or no probability that the store will fly. Thus this speed can be used for determinati a safe first flight test point.

5.3 Role of Experience In Structuring Mission Summaries

There is no substitute for experience. The separation engineer must be familiar with t e general flowfield characteristics of the aircraft. Once this experience is gained, certain genera rules can be followed to establish mission profiles regardless of the store being released. For example, regardless of what the predictions show, flight test experience has proved that on the A-10 a dramatic increase in nose-down pitching motion usually occurs for stores released from any stat of the aircraft at speeds above 350 KCAS. Just about any stable store released at 350 KCAS or be exhibits safe separation characteristics. However, above 350 KCAS, store nose-down pitching moti increases dramatically, such as the trend shown in Figure 26. For this reason, missions are usual performed at 375 KCAS. Similarly, when releasing stores from the F-15, there is a unique "Mach effect" between certain Mach numbers that was discovered quite by accident during a rather compreh e wind tunnel test program. As a result, testing of this Mach effect is built into all F-15 test p rams because of its significance (causes nose-up store pitching motions in a certain part of the flight envelope). One last example is on the A-7D. Stores released from the aft inboard station of a mul le ejector rack on the center pylon always translate inboard and pass under the fuselage; sometimes, closely. To summarize, even if one has a huge volume of predictive data, one may not know just v do with it! To be safe, the inexperienced engineer could plan many missions, expanding the fligh envelope very slowly. At least this would be better than pressing on to the edge of the envelope hoping that the predictions are correct. If they are not, an accident may result. But with experi e the mission summary process flows rather smoothly since the general characteristics of the aircraft e usually unchanged regardless of which store is inserted in the flowfield. This is because the aircraft flowfield dominates the store and not the reverse. Experience is the key ingredient necessary to arrive at the performance factor mentioned earlier in this section. The authors wish the reader could be given a cookbook for building a mission summary, but quite frankly it cannot be done. The inexperienced separation engineer (inexperienced from the standpoint of applying predictions to flight test and not inexperienced in making predictions) is well advised to proceed cautiously until total familiarity with the aircraft is achieved. Then the number of missions required can be reduced safely for subsequent programs. Go/no-go criteria should always be used between missions. For the authors' purposes, the collision boundary charts do this because, if predictions do not match actual results to the extent expected, the program is halted.

Before closing this section, one last point needs to be made on the concept of "know your airplane". From time to time the authors have mentioned that prediction methods have not been found to be of much value for ripple store releases (which is an almost constant requirement during operational conditions). It takes experience to know how to structure a test mission summary to proceed from single releases of a store to the minimum ripple interval release of all stores. Without experience, one would be advised to start with a release interval of no less than 1000 milliseconds and work down in increments (perhaps, 500, 250, 125, and 60 if this is the minimum value goal). Usually, the store-to-store interference effects are not predictable during ripple releases at low intervals, and a brute force approach is called for after safe separation has been established for single releases.

Lastly, assume that predictions show such superior separation characteristics that the separation engineer does not believe that even a single mission is required. In other words, the store can be certified with almost complete confidence from a safety of flight standpoint. The authors would caution that for demonstration purposes, at least one mission should always be performed. This mission is usually a small price to pay to corroborate those glowing predictions and to ensure that, once the store is certified and in operational use, there will be no surprises. This is not to say that if many configurations are required to be certified, every configuration needs to be tested. This is not the case. But at least the worst case configuration should be tested to show that the store was safely carried and released (with all associated fuzing, arming wires and/or other items required). This last point about testing with associated fuzes, arming wires and lanyards installed cannot be over emphasized. This is almost never done unless the testing organization is a military one - and even then it is not always done. During combat, the USAF encountered innumerable instances where fuzes did not work, arming wires did not withdraw properly or became entangled with ejector pistons and swaybraces on the ejector unit, or other unexpected events occurred during store separation. Close examination of the circumstances unearthed the fact that, in almost every case, the store was cleared for operational use by a test which did not include actually installing fuzes and hooking up arming wires and lanyards. Since the late 1960's, the USAF has made it a policy to always test stores for certification with inert fuzes and/or arming wires installed, and the problems previously experienced in combat have not recurred.

6.0 FLIGHT TEST PREPARATIONS

6.1 Purpose of Comparing Flight Test Results With Analyses

The prediction of store separation trajectories, whether from theoretical or empirical methods, is not an exact science. At best, it is an art, heavily dependent on experience. If store separation prediction methods were exact, then there would be no need for flight testing. However, since some flight testing is necessary and universally regarded as expensive and dangerous, it follows that such flight tests should be kept to a minimum with flight safety being the overriding factor. In general, store separation flight testing should be performed to validate the results of pre-flight prediction analyses, to complement the analyses in areas where predictive methods are not particularly useful, (such as ripple release of stores from several stations), and to document the results of the store separations.

Many hundreds of store separation trajectories may be generated by predictive methods for less than the cost of one flight test mission. If the results from a flight test separation of a store were known accurately and in detail, these flight test data could be used to validate the prediction method. While the validation of the prediction at only one or two sets of flight conditions will not validate the entire store separation envelope, it does give the store separation engineer (and managers) confidence that the entire prediction method is correct, and it allows fewer actual flight test data points to be selected. Even if flight test results do not match predictions, the engineer can generally mathematically manipulate the data base, forcing the prediction to match the actual test results. This allows additional predictions to be made, using each flight test result to update the prediction data base. Subsequent predictions will always be of higher confidence, again allowing a cutting back of flight testing. It should be stressed, however, that the flight tests so eliminated will always be "build- up" points. The outer corners of the allowable store separation envelope should usually be demonstrated in flight tests. These are likely to be the most dangerous spots in the envelope and these points should not be cleared for everyday use by operational pilots without first having the points demonstrated by test pilots using instrumented aircraft. In fact, the envelope demonstrated by store separation flight testing should be slightly larger than that cleared for operational use to allow for slight off-condition drops experienced in everyday operational flying. This may not always be possible; however, if flight tests have been used to validate store separation predictions throughout the allowable envelope, the predictions can then be used to investigate just how sensitive the outer boundaries of the allowable separation envelope really are. If for example, predictions show that a store may be separated safely at speeds up to 600 KCAS, then the store should be cleared to a lesser speed, say 575 KCAS, as a margin of safety. The margin of safety depends upon the aircraft and the release maneuver. The margin of safety can be very small if the store is to be released in level flight. On the other hand, the margin of safety might need to be considerable if the store is to be released in a sixty degree dive. In a similar vein, stores should not be cleared for separation at the edge of the carriage envelope. For example, if the carriage envelope were 600 KCAS, one should not clear stores release to 600 KCAS in a sixty degree dive. If many stores are being carried and released together in a ripple mode, the first store might be released at 600 KCAS but in all likelihood subsequent stores would be released at higher speeds due to the fact that the aircraft's speed would likely increase during the steep dive as more and more stores were released. For example, in general, the carriage envelope of the A-7D with external stores is 600 KCAS. Since stores are routinely released in dive angles up to sixty degrees, the store separation envelope is limited to 550 KCAS as a margin of safety to prevent overshoot of the carriage envelope. Similarly, the carriage envelope for the A-10A with external stores is generally 450 KCAS and the store separation envelope is limited to 420 KCAS. If stores are to be released in level flight, there is little need for a margin of safety since the aircraft's speed would not abruptly change as stores are released.

As store separation prediction methods become more sophisticated more accurate and most importantly, more reliable, even less flight testing may be required for validation. It is highly doubtful, however, if it will ever be a good policy to eliminate all flight testing, no matter what the state of the art becomes in store separation prediction.

6.2 Analysis Requirements

The foregoing discussion on reducing flight testing by comparing flight test data to predictions assumes that accurate and detailed flight test data can be obtained. In order to be useful in comparing actual data to predictions, the flight test data should include the following as a minimum:

Store Mass Properties: Store weight, center of gravity and moments of inertia. These should be accurately determined prior to flight testing for each store released.

Aircraft Flight Conditions at Store Release: Altitude, airspeed, Mach number, attitude (dive, pitch, yaw and roll angle), vertical and lateral accelerations, and time correlation with the stores released.

Detailed Store Separation Trajectory Data: Store roll, pitch and yaw angles and vertical, lateral, and longitudinal displacements with respect to the store's initial captive carriage position as a function of time.

Many of those involved in flight testing make the erroneous assumption that only detailed store separation data are necessary. This is not true. The aircraft flight conditions at release and the stores actual mass properties are equally important. Some years ago, a large US aircraft company was conducting store separation flight tests from one of its new aircraft. The stores to be released were ordinary inert 500 pound bombs. To simulate the actual stores, the bomb cases were filled with wet sand to the proper weight and center of gravity and then scaled. Unfortunately, by flight test time (several days afterward), the water in the sand had evaporated due to heating by the sun leaving the bomb cases now only partially filled with dry shifting sand. On release at 550 KCAS; some of the stores actually flew over the top of the aircraft's vertical tail! Some stores hit the aircraft's horizontal tail causing substantial damage. Engineers could not understand how their store separation predictions could have been so erroneous until some of the remaining stores were examined (by chance) and found to be forty percent too light and have an unspecified center of gravity due to the shifting sand fill. As a matter of routine, the USAF always fills inert bombs with concrete, taking care to achieve the proper weight and center of gravity.

Aircraft flight conditions at release are equally important if the store separation is to be compared with predictions. If the release is to be made at a specific altitude, in level unacceleral flight, it is fairly easy for the test pilot to release stores at the required conditions. However, even if an experienced test pilot is asked to release stores at exactly 8000 feet, at exactly 550 K in exactly a sixty degree dive, it is very likely that one or more parameters will be off-conditio Given enough practice, the pilot can become proficient at that set of conditions. However, it is a difficult task and a large amount of practice is not usually practical or available. Again, in stra and level unaccelerated flight, the pilot may be able to record his actual conditions accurately. example; 8040 feet at 555 KCAS instead of at 8000 feet at 550 KCAS, because parameters are not cha rapidly. However, if the pilot is in a sixty degree dive at a high rate of speed, there is little to scan all of the instruments to record exact release conditions, and as mentioned earlier, exact release conditions must be known to accurately compare actual flight test results with predictions

For these reasons, an accurate ground system should be available for pre-flight store property determination, and the aircraft should be instrumented to enable actual flight conditions stores release to be recorded. Appendix C describes the Precision Measurement Facility - called t "BIG-I" - which was specially constructed to accurately measure store mass properties at Eglin AF This description was prepared especially for this report and, hopefully, will be of interest to re s who wish details on the actual operation of the system.

When it is absolutely impossible to install sophisticated instrumentation, an over-the-shoulder cockpit camera can be, and has been, used with a fair degree of success. Unless the cam s an automatic lens aperture, the results will usually be less than satisfactory. In addition, the aircraft should be equipped with an onboard camera system to record store trajectories. The allo accuracies of these systems are very important if realistic comparisons between actual results and predictions are to be made. Although there are no hard and fast rules, the authors offer the foll tolerances as being what we would desire:

Store Mass Properties:

Weight	± 1%
Center of gravity	± 0.25 inch
Moments of inertia	± 1%

Aircraft Flight Conditions at Stores Release:

Altitude	± 50 feet
Airspeed	± 5 KCAS
Dive and roll angles	± 2 degrees
Acceleration in all axes	± 0.01 "g"
Yaw angle	± 1 degree

Store Trajectory Data:

Angular measurements in all axes	± 2 degrees
Linear measurements in all axes	± 1 inch
Time	± 0.01 seconds

The above tolerances are not hard and fast values. That is, if data obtained is slightly outside of the given values, it is not thrown out completely. Rather, the tolerances are desired - those used to design the particular instrumentation system. This is particularly true in the store trajectory data area. There have been many times where store trajectory data of even the accuracy specified was not necessary for adequate trajectory analyses. One should strive for the accuracy necessary to perform the task at hand - and no more! Engineers are used to working with exact figures, and these figures usually bear no relation to the level of difficulty in obtaining their exactness. For example, the tolerances given above for store mass property measurements are fairly stringent; however, using almost any modern measurement device, they are relatively easy to obtain. On the other hand, the detailed store trajectory data tolerances may seem to some to be inordinarily sloppy. But, they are as tight as is needed to determine safe reliable separation of the store. Requiring more stringent accuracy may necessitate a costly and sophisticated instrumentation and data reduction system that is just not needed.

6.3 Camera Requirements

At the very heart of obtaining detailed store separation trajectory data lies the camera. Selection of the proper film, camera, frame rate, lens, aperture, and camera locations are all extremely important. The recent advent on the scene of modern digital television cameras and their special needs will be discussed separately later.

Film:

Film is a users choice situation. Many organizations performing store separation testing use black and white film. Others use color. In the United States, some organizations, such as the Navy, frequently use the negative of black and white film for analysis purposes. Detailed analysis of such events as arming wire withdrawal from fuzes and fuze activation (for fuzes that function by rotating airdriven vanes) can be seen much clearer on color film than on black and white film. Color film also allows much more detailed store motion analysis because of the different contrasts and shadings available. However, there are many instances where black and white film can be used adequately. Choice of film type should then be dictated primarily by the data needed.

Camera:

There is almost universal agreement that 16mm movie cameras should be used. Manufacturers of such cameras, however, produce cameras ranging in size from that of a pack of cigarettes to those which weigh over twenty pounds and are very large and bulky. Each of these sizes has its use, and the choice is usually dictated by the camera installation location. The same is true of lenses. The camera location on the aircraft relative to the store being photographed will likely dictate the choice of the lens and its focal length. If possible, due to space and location requirements, the camera lens should have an automatic aperture capability. It is almost impossible to predict, on the ground, what light conditions will be best at the time of stores release. Even a one "f" stop error can cause the film to be totally unusable for data reduction. Automatic light compensating lenses are now available that are much smaller than those used in the past and can be installed in many locations which heretofore have been impossible. No matter which brand or size of camera and lens is selected, it is extremely important to realize that there are many large and small errors that must be compensated for if the film is to be analyzed. Almost everyone in the flight test profession recognizes that a particular camera body and lens combination must be calibrated. If one changes lenses, the installation must be recalibrated. Again, most people know that some lenses distort the image on the film and that this distortion can also be calibrated. However, there are other very important sources of errors in cameras that must be accounted for if quality data is to be obtained from the film. One of these errors is the possible offset between the physical and optical centers that has been manufactured into each separate camera. A complete discussion of all of these errors and how to compensate for them may be found in Reference (59). Another good discussion is contained in Reference (60).

Frame Rate:

There are many frame rates from which to choose. However, 200 frames per second is recommended as the optimum for store separation analyses. A typical store will travel from its captive carriage position to the bottom of the camera's view in 0.2 to 0.4 seconds (depending on the camera to store distance and lens). At 200 frames per second, this will produce 40 to 80 frames of usable data. Since most lenses have some distortion at their outer perimeter, the last few frames may be questionable. If the store is a heavy, high-density stable store, most frames will be more than adequate for analysis. If the store is light and relatively unstable and moves rapidly, most frames may only be barely adequate. Camera speeds below 200 frames per second are generally unsuitable for producing data analysis quality film, but may be used for documentary or quick look purposes. Frame rates above 200 frames per second are generally unnecessary in terms of store motion requirements, and are very expensive in terms of film use. This is of particular importance if the camera has a fixed film capacity. In effect, film may be inadequate for many passes on the same mission and this may necessitate additional missions. It is mandatory for cameras to be energized before the store separates so that the camera will be up to its operating speed and running smoothly when the release occurs. In the United States, the USAF has developed an instrumentation package which, when the store release button is depressed, sends the electrical firing signal first to the cameras and then, after about 0.5 seconds (this is adjustable), to the store ejector rack. The 0.5 seconds delay has proven adequate to allow camera speed-up but is not long enough to affect the pilot's action after the release button is depressed.

Camera Positioning:

Store separation trajectories can be recorded with cameras mounted externally on the parent aircraft, with a camera handheld on a chase aircraft, or with ground mounted cameras. Use of cameras mounted on the parent aircraft is by far the dominant method used. Ground based cameras are primarily used for store ballistic purposes. Chase aircraft cameras are used primarily as a back-up to the parent aircraft cameras, for special purposes such as to record missile-aircraft exhaust plume characteristics, or to record "ripple" stores release. In general, chase photography is used to record events normally out of the field of view of the onboard cameras.

The position of the aircraft mounted cameras is usually dictated by the geometry of the aircraft store installation. Ideally, cameras should be mounted directly to the side, front, and rear of the stores, however, this is frequently not possible for a variety of reasons. For example, adjacent pylons and stores may interfere with the mounting of cameras. Specifically, if stores are released from an inboard wing pylon, a camera mounted on the wing tip may not be able to view the store due to stores mounted on intermediate pylons which block the view. Also, the swept wing geometry of most modern jet aircraft prevents ideal positioning of cameras. The need to avoid mounting cameras in positions which would disturb the normal aircraft flowfield further limits the choice for mounting locations. Whatever their position, the cameras themselves should not alter or influence the store separation trajectory. It cannot be over emphasized that cameras must not disturb the aircraft flowfield. To the casual observer, it might not seem that wing mounted cameras can affect stores separated from adjacent wing pylons, but they can. Recent USAF flight testing has shown conclusively that the presence of wing tip cameras affects store separation in certain flight regimes. The only recourse in this event is to remove the cameras at the sacrifice of photo coverage rather than to degrade accuracy.

There is no optimum number of aircraft mounted cameras or locations. Some testing organizations use three or four locations. Others, up to two dozen! Figure 29 shows the camera locations selected by McDonnell Douglas Corp for use on the F-15. This multiple, redundant, location selection is typical of most aircraft contractor flight test departments. It should be stressed that not all positions are used simultaneously. The aircraft is wired and mechanically modified to allow cameras to be placed at any or all of those locations on any given mission. Normally, however, no more than eight cameras are activated. Figure 30 shows a close-up of the outboard F-15 wing mounted camera pylon. This is a special pylon built just to carry cameras and is used only for this purpose. Note that one camera is attached to the pylon in the photo. Two additional cameras could be mounted to this pylon at different orientations if needed. Figure 31 shows a rear fuselage camera mounted on the F-15. This camera is set to study fin opening of the MK-20 Rockeye. This store is not stable until the fins are open, and they do not open until an arming lanyard is pulled on separation. This condition has led this store to be an extremely critical item in separating from any aircraft. This is why an extra camera is specifically focused to record this critical event. Figure 32 shows another camera mounted on the F-15 which is also set to record the fin opening event on the MK-20. Note that the camera and its wiring are exposed to the airstream although the camera itself is sealed. Such external mountings have been used routinely by the USAF for years at speeds up to 700 KCAS.

Figure 33 shows a double camera mounting on the nose of an A-10 aircraft looking down an aft. This is an excellent view showing details of the fully exposed mounting. Note the azimuth pl for accurate positioning. Figure 34 shows a good example of an externally mounted wing camera on t 10. Here, unlike the F-15 wing cameras which were mounted on their own pylon, the camera is partia[illegible] embedded in the wing. The A-10 does not have an excess of engine power and camera drag degrades aircraft speed performance; hence, the semi-submerged mount. This figure also depicts the problem of releasing stores from several adjacent pylons. If, for example, the store closest to the camera in the figure was not dropped, stores on the other, more inboard pylons, could not be photographed easily since part of each store is obstructed by those more outboard.

Figure 35 is a good example of a camera which, because of its position, must be encl[illegible] in a shroud. The figure shows a camera mounted on the fuselage of an F-16 just aft and outboard of the engine inlet. It looks outward and downward only and cannot be adjusted, but it provides a good view of the inboard wing pylon. Figure 36 shows a unique and imaginative method of camera mounting. One has to look close to even see it! The F-16 wing is very thin, flexible, and has a short span. Mounting of a camera on the outboard portion of the wing (or on a pylon) proved to be unfeasible. Then, it was realized that AIM-9 missiles are carried on practically every mission. Even though the AIM-9 is only five inches in diameter, a small 16mm camera was found and mounted looking forward inside a d[illegible]y AIM-9 (real AIM-9 shell but with the missile components removed). A 45 degree mirror was then placed in front of the camera lens, allowing it to look out at 90 degrees directly toward the pylon with an unobstructed view. Only a small round hole is visible on the missile's surface. The entire dummy missile was carefully ballasted so that it simulated an actual AIM-9. As a result, the dummy missile had no impact on the aircraft's captive carriage envelope. Such installations have been used by the USAF before but never in such a small size. This installation was designed by General Dynamics Corporation and has been used during the entire F-16 flight test.

Figure 37 shows the wing and aft camera mounts on the A-70. Note the rather unusual, and seemingly flimsy, mount for the wing camera. In actuality this mount is strong enough to allow carriage to aircraft limits. There is one obvious disadvantage with this mount and that is its high drag. Flight tests have confirmed that the wing cameras/mounts reduce the aircraft's top speed by about 50 knots. Incidentally, the wing camera is a Photosonic with a 400 foot film magazine and the fuselage camera is a Millikan with a 200 foot film magazine.

Although the figures presented do not cover all possible types of camera mountings, they do illustrate the most commonly used types, and even a show a few mountings that are unique. Obviously, if one is going to photograph a store being separated from an aircraft and then run that film through some sort of data processing scheme to produce six degree of freedom digital trajectory data, it would be very desireable if one view could look directly at the store to be separated at 90 degrees from the store's longitudinal axis. Most of the action occurs in the longitudinal-vertical plane and this view is best for that. The more this view departs from 90 degrees, the more likely it will be that errors are introduced into some parameters while others could be improved. For example, even though a good perpendicular view of the longitudinal-vertical plane is desirable, this view does not give a very good resolution of what the store is doing in the lateral plane (towards or away from the camera). For this resolution, a view looking at the store from a 45 degree angle is better. In the USAF it is common practice to film most store separations from one or two aircraft mounted cameras, plus one chase aircraft. In most aircraft companies at least six cameras are generally used to photograph each release from various angles. Despite the number of camera views, only one or two sets of film are reduced to produce actual six degree of freedom digital store trajectory data.

Before closing this section, several points on the selection of camera mounting installations should be reiterated. First, so long as the aircraft has adequate power and so long as the camera installation does not adversely impact the aircraft carriage envelope, external mounting is much preferred since this is a simplier installation and easier to maintain. If either of these conditions are not met, then internal mounting (like the F-16/AIM-9) or semi-submerged mounting (like the A-10/wing) should be used. The point is that addition of external cameras must be planned and engineered onto the aircraft and not just added as an after thought when it is too late to develop an alternative installation without delaying the flight test program.

6.4 Video Cameras

All of the discussion heretofore has concerned ordinary 16mm movie cameras using film. However, within the past several years, a new phenonomen has begun to occur. Video, or television, cameras have long been dreamed of to replace the 16mm flim cameras. But, because of the very nature of a television camera using a vidicon tube and producing a television signal, the number of complete television pictures produced per second has been limited to a maximum of 50 to 60 (depending on whether a 50 or 60 Hertz television standard was used). This is too low for adequate analysis of store separation trajectories. Now beginning to appear on the scene are various versions of digital video cameras which do not produce television images through a vidicon tube, and are not limited to the 50 to 60 fields per second (this term, common to television, can be equated for our purposes to a movie camera's speed in frames per second).

The United Kingdom at Boscombe Down, has pioneered the use of one such video camera - a Charge Coupled Device (CCD) camera made by the English Electric Valve Company Limited (model P4320).

Simultaneously, the United States Navy at Patuxent River, Maryland, has been evaluating a video camera made in Japan and marketed by the Instrumentation Marketing Corporation of California. the CCD camera developed in the United Kingdom will produce a complete field (or frame) in 1/1000 of a second, so it will stop almost any action with a very clear view. However, only 60 of so of these 1/1000 or a second "snapshots" may be produced in a second. It is a very small and compact camera which uses solid state circuitry throughout to produce black and white video images. Eglin Air Force Base has just purchased one of these cameras and has begin evaluation of store separation using the camera. Although we do not believe this particular CCD camera will be able to completely replace 16mm movie cameras, we do believe it will allow us to write a specification for what we want in a video camera. The Navy evaluation of the Japanese camera has produced good results. When the Japanese video camera is tied to a specially modified video cassette recorder, true camera speeds of up to 200 frames per second can be televised, recorded, and played back at that speed. The Air Force plans to explore this equipment within the next year. Neither camera under test has an automatic exposure setting lens.

Figure 38 shows the English Electric Valve company Video camera. This camera is only 196mm long, including lens, and is 66mm square. It only weighs 868 grams, including the lens. Figure 39 shows the Japanese camera referred to earlier. It is 224mm long, 90mm wide, and 114mm high, including lens. It weighs only 2043 grams.

Video systems promise to revolutionalize flight test documentation. At a busy flight test facility such as Eglin Air Force Base, it has been conservatively estimated that video systems will save hundreds of thousands of dollars each year over movie film systems. This savings occurs in not having to buy and process enormous quantities of movie film in order to get small strips of usable data and also in the avoidance of flying many missions. With a video camera, telemetry system, and video recorder, engineers may view the store separation trajectory immediately and repeatedly. Then, engineers may contact the pilot and tell him that the separation looked good (as predicted) and authorize him to proceed to the next test point. Thus, many releases can be performed on the same mission which will reduce the total number of missions required for each program. Such a process is not possible today using film cameras, and it is in the area of mission avoidance that the video system really has potential for cost savings. Test reports of the United Kingdom camera prepared for the Royal Air Force by Boscombe Down are contained in References (61) and (62).

6.5 Data Reduction Techniques for Cameras

6.5.1 Techniques Available

If cameras, whether video or film, are used to obtain slow motion views of the store during separation from the aircraft, then this optical data must be reduced to angular positions and displacements versus time for comparison to predictions. Basic to this solution is the knowledge of the camera's position in relation to the store being released. If the camera's distance and angular position relative to the store are accurately determined, and a known point or distance on the aircraft appears in every frame of the camera's view, then a mathematical solution may be obtained for successive positions of the store during separation. This mathematical solution lies at the heart of every data reduction technique now available. How this solution is obtained varies considerably from technique to technique. The earliest solution used for store separation data reduction involved a purely mathematical triangulation process. Although the actual program developed by different agencies or nations varied in name, they could all be described by the term "photogrammetry" - or a photogrammetric solution of the time-space-position problem. Photogrammetric techniques require complex accurate painting patterns on both the store and portions or the aircraft, as well as manipulation of the data obtained in complex equations. Later improvements of these photogrammetric techniques lessened or eliminated some of the painting patterns, and simplified somewhat, the data manipulations.

In the late 1970's, the United States Navy developed a photo-imaging technique called the Photo Data Analysis System (PDAS). This provided a major improvement over photogrammetric techniques in that no special paint pattern of either the store or the aircraft was required. PDAS did, however, require the purchasing of some unique data reduction hardware and the training of personnel to operate the equipment. After the one-time purchase of equipment, PDAS provided a significant reduction in the time and cost for data reduction. It also provided an improvement in data accuracy. PDAS has since been widely used by both the Navy, Air Force and several US aircraft companies. Because of its inherent advantages in low cost and quick data turn-around, a group was formed in the US to seek improvements to the PDAS. In the mid 70's, efforts resulted in a second generation photo-imaging technique called Graphic Attitude Determining System (GADS). It too required the purchase of a unique machine for data reduction and the training of operators, and has been in use at Eglin AFB for several years.

Another type of data reduction technique allows the viewing cameras to be located on a photochase aircraft instead of on the releasing aircraft. This technique, called CHASE by its developers at MacDonnell Douglas Aircraft Company is highly complex, requires an inordinate amount of pre-flight calibration efforts and many baseline camera runs. But, CHASE does completely free the release aircraft from camera carriage, and the actual reduction of data is relatively straight forward. Because of its complexity, it would be of use only to large, well funded flight test organizations. It offers an excellent quality alternative to the more conventional data reduction techniques. In the following paragraphs, each of these data reduction techniques will be discussed in more detail.

6.5.2 Photogrammetric Techniques

By far the most commonly used technique for the reduction of movie camera film is the photogrammetric method. It is used by virtually every government agency and industry within NATO. Although the detailed description of each nation's, or each company's, use of the photogrammetric technique varies, the basic method remains the same. In this method, both the store being released and the aircraft pylon are painted with a background color and a contrasting color pattern of dots whose positions are accurately known with respect to some specific point. Figure 40 shows a typical paint pattern. Size and color of the dots are not fixed; they are optimized for accuracy and ease of film reading. However, a minimum number of dots must be visible at all times in the film. Onboard camera lenses are selected so that both the store being released and part of the aircraft's adjacent structure (such as the pylon) are visible on the film. After the release, each frame of the onboard gathered movie film is processed through a film reader manually. These data, along with a series of geometric and physical constants, such as location of the reference dots with respect to a specific position, camera location and lens focal length, are input to a computer. The computer is programmed to solve the equations of motion and defines the store trajectory, printing out angular and linear motions as a function of time. Although a two-camera solution is preferable, a one-camera solution can be used most of the time and will provide accuracies of about ± 2 inches for displacements and ± 2 degrees for angular motions. The photogrammetric computer program requires starting estimates of the store and a camera orientation with respect to the aircraft. A final iterated solution is then obtained which achieves convergence for even poor starting values. After the first frame, the program employs previous frame results as the estimate for the suceeding frame. Because of this, wing flexure and vibration are automatically eliminated. The computer is programmed to print out the trajectories in both tabular and plotted format, so that a direct comparison may be made between predicted and in flight trajectories.

Variations of the basic method, which are widespreed, include the use of a geometric paint pattern on the store instead of rows of dots (Figure 41), the elimination of painted dots or references on the release aircraft, and the automatic reading of the film by machine. A good basic description of the photogrammetric data reduction process may be found in Reference (63). Utilizing the improvements mentioned earlier, several agencies have been quite successful in the employment of the photogrammetric technique. Any reader desiring to learn more about the employment of this technique should consult the NLR report at Reference (60). It is a basic handbook for the user of the technique and is an excellent source document. Another excellent source document for the reader who wishes to delve deeply into the actual mathematical representations of the equations of motion is the NLR report at Reference (64). A typical set of film strips obtained by NLR for data reduction is shown in Figure 42. Figure 42 also shows the value of having an automatic exposure camera lens. Note the difficulty in reading the right-hand strip versus the left one - all obtained under similar conditions. Had an automatic lens been available, the quality of the images would have been more uniform and data reduction greatly facilitated. Reference (65) contains a description of an automated film reader which asserts that it is ten times faster and seven times more accurate than manual film reading. It is a computer controlled system specifically designed for the analysis of pictoral data. This system reduces the data reduction time, a major drawback of the basic photogrammetric process.

An interesting report on the inherent accuracy of a single-camera photogrammetric solution to the store separation problem is given in Reference (66). In this report, an actual store (an empty rocket pod) was set up in a hangar on very accurate mountings and then, using a surveyor's transit, was moved through a known set of displacements and angles, being photographed at every step using a 35mm camera. The resulting 35mm slides were then used as the frames of a movie would be and run through the photogrammetric computer solution of the equations of motion. Over 900 photos were taken and processed, and both the accuracy of the photogrammetric method and optimum camera angles for obtaining best solutions were established.

6.5.3 Photo Imaging Techniques

PDAS

The first major alternative to photogrammetric data reduction techniques was developed by the US Navy in the 1960's and, as mentioned earlier, is called PDAS. It offered the major advantages of not requiring any painting of the store or aircraft, reduced data reduction time, and enhanced accuracy. The USAF also adopted this method in the early 1970's in support of the A-10 and F-15 store separation flight test programs. On the one program, the A-10, because of the large number of aircraft pylons (eleven) carrying stores, many hundreds of stores would have had to be painted with a highly accurate paint pattern if the usual photogrammetric technique had been used. Because of the accuracy of painting required, the lack of adequate painting facilities, and the large number of stores involved, just painting the stores would have taken months. By adopting the PDAS technique, flight tests were simplified and a large cost and time factor was eliminated.

PDAS utilizes an image matching technique to obtain spatial position and orientation of photographed objects with respect to recording cameras (Figure 43). It consists of projecting each frame of the onboard flight gathered data film through an optical system into a high resolution video camera and displaying the resulting image on a television monitor located on an operator's console. Another high resolution video camera is positioned near the console to view an exact scale model of the store. The store model is mounted on a remotely controlled six-degree-of-freedom model positioner mechanism. The video signal from this second television camera is fed through a video mixer and the resulting image is simultaneously displayed on the same television monitor as that from the data film. The operator can adjust the position and orientation of the store model through the use of a set of levers on the console. The store model is adjusted by the operator until the image of the store on the positioner is exactly superimposed on the image of the store from the data film (a process similar to using a camera range finder). Once the two images are exactly aligned and superimposed, the operator presses a button which transfers the encoded frame count and position data to a computer data card. Each frame of the film is similarly reduced, until a card deck is generated. This deck is input to a computer program - just as in the photogrammetry process - to solve the spatial relationships. The output from the photo-imaging technique is a set of tabular data and selected plots which accurately define the store separation trajectory to compare directly with predictions. This technique produces extremely accurate data (± 0.1 foot for displacement and ± 1.0 degree for angles). Because PDAS does not require painting of the stores, the overall cost of data reduction is less than one-half the cost of data reduction using photogrammetry.

At the time the USAF decided to adopt the PDAS technique, only two systems existed - one at the Navy Pacific Missile Test Center, Point Mugu, California, and the other at the Naval Weapon Center, China Lake, California. The system at Point Mugu was chosen for the A-10 and F-15 programs. The PDAS lived up to every expectation. During the course of the A-10 and F-15 programs, improvements in output data format were made. Specifically, pictorial computer-generated trajectories were created. A sample of the PDAS graphical trajectory output is shown on Figure 44. Data reduction time was indeed shortened, and the data quality for several hundred store releases over a two year time span was excellent. As the PDAS became used in quantity, even the cost per run of reduced store separation data was lowered to a value significantly lower than that of a comparable photogrammetric trajectory. A complete detailed description of the Point Mugu PDAS can be found in Reference (67).

GADS:

Although the USAF and US Navy were well satisfied with the results from PDAS, both services recognized that considerable improvements could be made - particularly with the availability of powerful, mini-computers. As a result, a working roup was formed to incorporate all these desired improvements into a specification, and this specification was then offered to industry (in 1978). The GADS, which emanated from this specification, was purchased and installed at Eglin AFB, Florida where it has been used for store separation data reduction activities in hundreds of tests. It has proven to be a major improvement to the PDAS technique. Unlike the PDAS which requires an exact scale model of each store to be placed on a manually operated positioning system, the GADS uses a self-control computer to generate a video image of the outline of the store, thereby eliminating both the mechanical positioning system of PDAS and the manufacture and storage of the exact scale models of the stores. The GADS also incorporates a much improved joy-stick-operated store image manipulation system, thereby making the operator's task easier and quicker. A photograph of the GADS equipment at Eglin is shown in Figure 45. During preparation of this report, the authors discovered that there had been no paper published which described in detail the operation of the GADS. Accordingly, a heretofore unpublished report of the GADS prepared for in-house use is included as Appendix D along with a sample of the data output taken for a MK-82 general purpose bomb released from an F-15 at 560 KCAS in a 62 degree dive.

Photo-chase Techniques

The above techniques all require cameras to be mounted on the aircraft releasing the stores. They also all depend for their accuracy in the exact knowledge of the geometrical relationship (angles and distances between the cameras and the store and the reference points. It was, therefore, quite a revelation when, in 1975, the McDonnell Douglas Company announced the development of a technique that positioned the cameras not on the release aircraft, but on the photochase aircraft! Since the exact distance between the photochase aircraft and the release aircraft could never be ascertained, the general testing community looked upon this new technique with great skepticism. However, the system, appropriately termed "CHASE", was proven during F-15 flight testing. A complete description of the technique can be found in Reference (59). The technique proved to be very successful, primarily through the results of some innovative mathematics, elimination of all assumptions, and very precise optical calibrations. However, it also proved to be a highly complex and demanding system to operate. It is still used upon occasion, but is not known to have been taken up by other testing organizations.

6.5.4 Consideration for Selection the Right Technique

There is one factor which must be stressed here. All of the methods described provided accurate and useful quantitative data, both in tabular and plotted format. We have run comparisons of the methods by processing the same film strip from a particular store release and comparing the output plots. No useful purpose could be served by presenting the comparison in this report as the superimposed data results in essentially the same line. This brings us to an important conclusion. We have examined several methods of reducing flight test data, the kinds described above, and others developed by various airframe manufacturers. All of them are inherently accurate enough to provide good, usable data. The degree of mathematical accuracy attained is not as important as how many of the error-causing factors are accounted for by the method, and whether the factors are compensated for or corrected. Data reduction accuracies of $\pm$ 2 or 3 inches and degrees can be absolutely adequate if the error-causing factors are corrected for. Of all the error-causing factors, the ones which seem to be the most important (and most difficult to correct) involve those connected with the camera optics. Errors caused by lens/camera alignment, calibration, internal manufacturing aberrations and uncertain optical centers are among the most important. Although great care must be exercised in developing a data reduction method which properly accounts for as many of the error-causing factors as is possible, equal care must be used in insuring that the method does not introduce other, larger errors through the human factor. A method which requires an inordinate amount of human input and manipulation of data prior to and during computer reduction is extremely prone to errors, particularly if no built-in-test features are incorporated.

From this discussion, one can see that there is no "right" or "wrong" technique. The right technique is the one that best fits the users requirements. The photogrammetric method requires no initial one-time outlay of funds for expensive data reduction equipment, but does require more time (both computer run time and workhours). It could be the "right" selection if store separation tests are not performed in large numbers. If the testing organization is a major activity, constantly producing large numbers of tests and data, then the purchase of the data reduction machine can be amortized over the large number of tests. In such a case, even with the cost of equipment, photo-imaging can provide data much quicker and at lower cost.

A word about video data processing. All the discussion above has assumed that the store separation data was acquired by 16mm movie film cameras. If, however, digital television cameras replace movie film cameras as the onboard data gatherer, then the reduction of this data offers even more alternatives. First, since the data is already in video format, a step in the GADS could be skipped (conversion from photograph to video) at a considerable cost savings and simplification. Also, the reading of the video data, since it was initially gathered in digital format - could be processed electronically. And, since this video image is now being superimposed by the GADS on anotner computer-generated video image of the store, all this could conceivably be processed by computer with no manual manipulation. This would indeed be an order of magnitude increase in the state of the art, and is not out of the realm of the foreseeable future. For the present, the United Kingdom at Boscombe Down is the only agency (to the authors' knowledge) processing video data, and their description of this may be found in References (61), (62) and (68).

7.0 COMPARING ACTUAL TEST RESULTS WITH PREOICTIONS

This section describes the basic approach used to compare actual flight test results w predictions during store separation testing and how subsequent flight test points are adjusted bas this comparison. Also discussed is an approach for performing "brute force" testing where one doe have any predictions per se (no analyses) - flight testing is planned and conducted based on expec store separation characteristics. Clearly, brute force testing must only be performed by experien personnel to minimize potential safety of flight hazards. In brute force testing, the experience judgment which come with experience are essential ingredients to a successful program.

7.1 Iterating Between Flight Test and Analyses

There are generally two levels of comparison. In the first level, flight test six degree of freedom digital trajectory data (obtained from GAOS or another data reduction system) are compared with digital predictions at each test point. If actual results (based on judgment) do not closely match predictions, subsequent test points may be adjusted from the original test plan. Between each test point, the predicted collision boundary is recomputed and adjusted to reflect actual test results to that point. Figure 46 shows the general process by which this is accomplished. Note that at the first test point actual test results exactly match predictions. Accordingly, the next test point would be performed as originally planned. At the second test point the store pitched nose-down slightly (judgment) more than predicted. In this case, test point three would also be performed as planned. However, in addition, the predicted collision boundary would be recomputed by fairing (extrapolation) of actual test results using predicted trends as a guide. Obviously, this requires engineering judgment. This process is performed between each test point and, as a result, the confidence as to the accuracy of the final collision boundary will ultimately approach 100%. Incidentally, before proceeding any further, the reader is reminded that the above process is also performed for store yawing and rolling motions. The process for these motions is identical to the pitching motion and is, therefore, not presented herein. For illustrative purposes, store pitching motion seems to be the easiest to describe, and this is why it was chosen. To continue, assume that results for test point three is as shown in Figure 46. Upon recomputing the collision boundary, it can be seen that the fourth point is outside the boundary. At this point, one of two things should be done: the test point should be adjusted to be inside the boundary, or if the fourth point is just inside the boundary, one might not conduct the test point. For example, assume that the last test point was at 480 knots and the recomputed collision boundary taking results up to this speed into account is 500 knots. In all likelihood, another test point at 500 knots should not be performed right at the predicted collision boundary. Oata could be extrapolated one more time and, assuming the recomputed boundary did not change (or changed very slightly) the maximum safe store separation would have been established speed without actually testing the final end point. But, if testing is performed very close to the end point, the end point might actually be tested if it happens to coincide with the collision boundary.

Now assume that the results at the second test point are as shown in Figure 47. In this case, the store pitched nose-down significantly more at test point two than predicted (judgment). At this point flight testing should either be stopped until additional analyses are performed, or the next test point adjusted to a much lower speed. It would be foolhardy to perform the next test point as planned because little confidence would exist as to the extrapolated trend. In most cases, the next test point should be adjusted to a lower speed and testing continued rather than to delay the test program. As stated earlier, practically all USAF programs must be completed in the shortest time possible (time is of the essence). For these USAF programs it has been proven that additional test points can be flown more quickly than the time it takes to perform additional analyses. Therefore, the test program is normally continued utilizing more test points. The rigorous engineering approach would, of course, be to perform additional analyses "anchoring" subsequent predictions on actual results to date. This is only done when one believes one cannot safely proceed to the next, closely spaced, test point safely. Such a case might be during the test of a lightweight or unstable store which has a known nose-up pitching motion trend. Here an error in selecting the next test point might cause the store to "fly" up and hit the aircraft. In a conservative test environment one would be ill-advised to take a chance on going to the next test point in the interest of expediency. Accordingly, testing should be stopped, additional analyses performed, and then the analyses used as a basis for selecting the next test point. The next test point might be the same point that one would have selected (a small increase in speed) without the benefit of analyses. However, the important difference now is that if one proceeds to the next test point and has a problem, everything possible would have been done from an engineering standpoint and judgment would have been eliminated in a critical test area. In short, there would be an audit trail to the next test point. To reiterate, the occasions in when such store separation motions for lightweight or unstable stores occurs is in the definite minority. In fact, the authors have not stopped a program to perform additional analyses because predictions did not closely match actual results for the last several years.

In the second level of comparison, predictions in a graphical format are compared with actual test results in a qualitative manner. The engineer compares predictions (normally generated using a computer graphics program) with the store separation trajectory obtained directly from the onboard movie film. In this method, the film is not reduced using GAOS or any other processing system. If in the engineer's judgment the actual store separation trajectory closely matches predictions, the next test point is performed. While this method requires an experienced engineer, it has been used with remarkable success. With proper training, one can generally do a very good job in estimating store angular motions at various estimated linear positions. By eliminating the data reduction step entirely, testing may be accelerated by a factor of two to three from one to two missions a week to at least five missions a week. The cost savings gained by eliminating the data reduction step is not a factor; the time savings is.

There is an intermediate level of comparison between full data reduction of onboard movie film and no reduction at all that is worth mentioning. The authors have frequently been in situations where no data reduction system is available (or one can assume that the GAOS or another system being used has broken down), and yet testing must go on. But at the same time, store separation motion is of concern to the engineer, and some hard data is needed to compare with predictions. In such a case, the film is commonly projected frame by frame on an appropriate blank piece of paper. The pylon and store are sketched in the captive carriage position as references. Then the film is simply advanced a specific number of frames (a stop action projector in conjunction with time-coded film is always used) and by tracing around the projected store image, the store is sketched in the new position. This process is continued to the extent necessary. When the store is in the captive carriage position it is usually very easy to locate its center of gravity. Assume in this example the center of gravity is between the carriage lugs as shown in Figure 48. The actual diamater of the store is known so the length of a store diameter sketched through the store center of gravity can be easily scaled and used as a reference length. In the second store position, assume that the carriage lugs are no longer visible (the store has rolled). Good judgment must now be used in locating the store center of gravity. One could draw in on the sketch a cross section of the store at the center of gravity in proper perspective to the orientation of the store. Subsequently, the center of gravity could be located as shown. The length of the line drawn through the center of gravity would now be compared to the actual reference diameter. The average of the scaled length from the last position (in this case the captive position) to the next position is used to arrive at the scaled length to make the vertical displacement calculation. For example, assume a true diameter of 18 inches (full scale) which is 1 inch when drawn on the paper. Then assume that in the separated position shown on the figure, the diameter is .9 inch. We would use an average diameter (drawing scale) of .95 inch. Further assuming the distance (drawing scale) between the store centers of gravity (captive position to separated position) is 0.5 inches, a ratio is applied to arrive at a full scale displacement of 9.47 inches. The process is continued, as mentioned earlier, as long as is necessary. The figure shows sketches that would be made from a wing tip camera. If the store separated with substantial yawing motion, store pitch should not be estimated from this camera position; an aft or forward fuselage mounted camera would be used. But, again assuming the ideal case of store pitch without appreciable store yaw, a protractor is simply used to measure the angular difference between the store longitudinal axis (one has to establish the store longitudinal axis by drawing a line as shown on the figure) and its original position . An important point is that displacement and angular values are always calculated with respect to the initial captive carriage position so a cumulative built-in error is not established. While all of the aforementioned discussion might appear simplistic to the reader, it must be emphasized that this method has been used successfully on innumerable occasions as an expediency when there is no other way to obtain hard data.

7.2 Brute Force Testing

In the previous section the authors discussed an approach for continuing testing when actual results do not match predictions. In this section an approach will be discussed for performing testing when no predictions exist at all. However, first some boundaries must be placed on what is defined as brute force testing. In the truest sense of the word, brute force testing would be to perform testing for a previously untested store without any prediction of what might happen. The authors would never perform such brute force testing since it would violate all of our requirements to maintain high safety of flight criteria. What is meant when brute force testing is referred to is the structuring and conduct of testing with a solid foundation based on past experience with similar stores and/or aircraft. The simplest example of "brute force" testing would be a store that is analogous to one that has already been flight tested and certified in the aircraft flight manual. Assume that the MK-82 low drag general purpose bomb (LDGP) with conical fins is certified on the A-7 and it is desired to certify the same bomb with retarded fins. Figure 49 shows a comparison of these bombs. They weigh about the same and are approximately the same length. A review of the free-stream aerodynamic characteristics of the two bombs would show that the MK-82 with the retarder fin (Snakeye) closed is slightly less stable than the MK-82 LDGP. Because of the relatively minor aerodynamic, physical, and geometric differences, the two bombs are considered analogous. Accordingly, without the benefit of hard predictions, but with the knowledge of the demonstrated separation characteristics of the MK-82 LDGP bomb, a brute force flight test would be performed for the MK-82 Snakeye.

The way time and money may be saved using the brute force method can best be illustrated with a few examples. During the initial test program of the MK-82 bomb on the A-7, extensive wind tunnel testing was performed using the CTS method, and then trajectories were validated by performing five release missions which cleared the store throughout the desired flight envelope (speed up to 500 knots and dive angles up to sixty degrees). By using the brute force method the MK-82 Snakeye was cleared (with the fins closed) in four missions. Even if time consuming wind tunnel and/or off-line analyses were performed prior to flight testing, it is doubtful that more than two missions would have been cut from the program. In all likelihood, only one mission would have been cut from the program. Between each mission, onboard film was reviewed quantitatively and since actual results matched expectations, testing was continued to a successful conclusion. Next, brute force testing was used to clear the MK-82 Snakeye for releases with the fins open. In this mode, a lanyard is extracted from the band which holds the fins closed and frees the fins to open after stores release. If CTS or grid wind tunnel testing were performed, a model of the store with the fins closed would be used first. Then, at the appropriate distance corresponding to the desired lanyard length, the tunnel would be shut down and a model with the fins open would be substituted. This is a time consuming and somewhat inaccurate process in that the transition of the fins between closed and fully opened is not tested. The time for this to occur on the real bomb varies with airspeed. At low speeds, the fins open only partially, and at high speeds the fins open fully, with attendant differences in the bomb's drag characteristics. Finally, if the lanyard length is changed, the wind tunnel data is compromised since in the wind tunnel only one lanyard length is normally simulated. For these reasons, it is easier to just go out and flight test (presuming we have experience with the functioning of the MK-82 Snakeye as a result of flight tests on another aircraft). An initial lanyard length is selected to allow the store to fall a safe distance below the aircraft. Sometimes a ground static ejection test is performed for the purpose of defining optimum lanyard lengths. Testing is begun at an aggressive speed since the store would already have been cleared with the fins in the closed mode. During the course of testing, the lanyard length may be adjusted, as needed. This was required during A-7 testing because fin opening at high speeds resulted in a flow disturbance over the aircraft's horizontal tail causing a severe aircraft reaction on the order of +5 to +7 "g"s. Accordingly, the lanyard length was adjusted until this problem was eliminated. To this day the authors are convinced that this problem would never have been uncovered during wind tunnel testing or during off-line analyses.

Another area in which brute force testing is used almost exclusively is in support of store separation from multiple bomb racks, and from multiple pylons in the ripple release mode. Except in the case of guided stores (e.g. the GBU-8, 10 and 12), practically all unguided stores (e.g. the MK-82LDGP, CBU-58 and MK-20) are operationally required to be released in the ripple mode. The reason for this is quite clear: one must release a large number of unguided stores, centered on the target, to increase the probability of target kill. Ripple release would not be a problem from a store separation standpoint were it not for the fact that, as a general rule, stores are required to be released in the minimum interval possible. Most multiple bomb racks such as the MER-10 and TER-9 can function (that is step from rack station to station) down to intervals as low as 50-70 milliseconds. In addition, most USAF aircraft can step from pylon-to-pylon in 20-30 milliseconds. These are small intervals that have large store separation ramifications. Unfortunately, the authors do not have confidence in the ability to model rack dynamics and store-to-store interference during ripple release, both of which can significantly affect store separation characteristics. Multiple bomb racks such as the MER-10 are quite flexible. This flexibility results in different effective ejection forces at each of the six rack stations. On one ground ejection test, six MK-82 inert bombs were ejected from a MER-10 at a low ripple release interval. From high speed photography, individual store ejection velocities were measured. Because of rack flexibility, velocities varied from a maximum of eight feet per second down to zero (the rack actually bent away from the store, and imparted no ejection force). Static ejection testing provides the force at each station for use in predictions but lack the effect of aerodynamic forces. Unfortunately, the force further varies with the weight of the stores loaded on the rack. To date a complete ejection force data bank for all of the aforementioned combinations of factors which impact ejection force does not exist in the USAF. The other major area mentioned earlier that causes considerable problems during ripple release is store-to-store interference. It should be readily apparent that when two stores are released from tandem (one behind the other) rack stations (as from a MER-10), the store released from the forward station disrupts the flowfield (in an unknown way) for the store released from the aft station immediately behind. When A-10 testing was being performed, it was found that stores released from the forward MER-10 stations separated with a strong nose-down pitching motion which caused the stores to translate rapidly aft resulting in nose-to-tail collisions with stores released from the aft MER-10 stations. The aft stores separated with a very mild nose-down pitching motion, and hence, little aft movement in the near field of the aircraft. The difference in the relative drag between the forward and aft stores due to the magnitude of the nose-down pitching motion was directly responsible for the collisions. However, predictions, using the grid method, showed that the aft stores would separate with the same nose-down magnitude as stores released from the forward stations. The reason the aft stores did not pitch nose-down as predicted was due, in our view, to the disturbed airflow caused by the forward separating stores. Using brute force, various combinations of interval and speed were tried and a combination that was acceptable for operational use was never found. That is, the low interval desired could never be successfully achieved at a high release speed. As a result of these tests, the MER-10 was never certified on the A-10. As the reader can see this can be a significant problem. Because of the unpredictable effects in situations similar to the above, the authors tend to rely on the brute force method. Our usual approach is to begin reduced interval testing at the end point condition where stores separation in the single mode has already been demonstrated. For example, on the A-10 safe release of the MK-82 LDGP bomb from the MER-10 was demonstrated at the maximum desired speed of 420 Knots in a 60 degree dive in the single mode. Then, at that same speed, releases were performed at progressively reduced intervals until the minimum interval was reached. Had a problem been encountered, airspeed would have been reduced and then testing would have been resumed at the last successful interval. This type of process should be continued until enough data are acquired to formulate a certification recommendation. In the case of the A-10, the authors had a choice of a 420 knot speed (with an interval which was determined to be too high for operational use) or a lower airspeed (which was also determined to be too low for operational use) with the minimum interval desired. The A-10 operational community did not want to back off from their requirements in terms of needing high speed and low interval and, therefore, as mentioned earlier, the MER-10 was deleted from the aircraft. To show how totally dependent store separation is on the aircraft's flowfield, it may be useful to mention that low interval releases of MK-82 LDGP bombs was demonstrated on the F-15 at speeds up to 700 knots without a single problem!

In addition to releases from an individual multiple bomb rack in the ripple mode, the store separation engineer must also consider possible store-to-store interference when releasing stores from multiple pylon stations. Most tactical aircraft have many pylons and these are normally all loaded with stores which are then released in a predetermined sequence from pylon-to-pylon. The A-10 has eleven pylons, the A-7 and F-16 have six, and the F-15 has three air-to-ground pylons, so the possibility of store-to-store contact is always present; particularly when stores are loaded and released from multiple bomb racks such as the MER-10 and TER-9 where shoulder stores are ejected at an approximate angle of 45 degrees from the vertical. Figure 50 shows a certified configuration of MK-82 LDGP bombs on the A-7. In the ripple pairs mode one bomb is released from each side of the aircraft simultaneously in the sequence shown. Note that the number 5 bomb is ejected towards the number 7 bomb which is released two intervals later (if the interval selected is 70 milliseconds, the number 7 bomb would be released 140 milliseconds after the number 5 bomb). The separation engineer must be aware that, under some conditions, the number 5 bomb may be below the number 7 bomb just as the number 7 bomb is ejected and the two may collide. In addition, the probability of collisions between stores released from opposite sides of the aircraft cannot be ignored. Consider the possibility of contact between the number 11 bomb on the left wing and the number 9 bomb on the right wing. It was mentioned in an earlier section that on the A-7, stores released from the aft inboard station of a MER-10 have a strong tendency to translate inboard towards the fuselage. Accordingly, stores released from these stations must be closely monitored. In short, it should be apparent that with thirty-two bombs released in a minimum interval, some store-to-store contact is likely to occur. In the authors opinion, the best way to establish the presence or absence of store-to-store contact with specific intervals is by brute force testing. It is recommended that the store separation engineer use a sketch such as shown in Figure 50 to highlight those rack and pylon stations where store-to-store contact is likely to occur. In this way, the scope of the test program can be structured to concentrate in this area. Once a safe interval has been established, then a full-up ripple release test where stores are released from all pylons can be performed as a demonstration. However, there is no need to release, in a case such as that on the A-7 configuration, all thirty-two bombs on every mission.

8.0 BALLISTIC TEST CONSIDERATIONS AND METHOOS:

It was mentioned in the beginning of this report that the ability to hit an intended target must be considered during all store separation programs. If the store separates from the aircraft satisfactorily but cannot be made to hit its intended target, the program is really a failure from an operational standpoint. In our experience, many people do not make ballistic analysis and testing an integral part of store separation test programs, and when they do, it is not performed in a rigorous manner..

In the OAC, the engineers who formulate and conduct store separation programs work closely with the engineers who develop store ballistic, safe escape, and delivery tables. This situation is fostered because all personnel are part of the same office and work in adjacent rooms. Because of this arrangment, whenever a new store separation program is started, ballistic analysis and testing is made an integral part of the program. Ballistic delivery and analysis engineers review each new program to determine whether or not additional data are required or if available data (for the same store but in a different carriage configuration and/or on a different aircraft) are adequate. When it is determined that additional data are required, ballistic delivery and analysis engineers work hand-in-hand with store separation engineers to structure a flight test program to obtain as much data as possible on a non-interference basis. In a great many cases, a majority of ballistic data are obtained in just this way. One can easily appreciate, therefore, the advantage of close cooperation between the groups of engineers.

In 1970, the USAF performed a theoretical study of the sensitivity of various parameters to ballistic accuracy for a number of conventional stores (Reference (69). The results of this study are quite interesting. Table IV was prepared by extracting data from the study results. The values in Table IV show that if a MK-82 LOGP store is released from a "generic" aircraft at 5000 feet (above the ground) in straight and level flight at 450 and 860 knots, maximum (if all of the sensitivity parameters are additive) miss distance on the ground is 501 and 1113 feet respectively! While the magnitude of these values are quite large, what is surprising is their source. Note that those parameters related to the aircraft flight conditions at release (altitude, airspeed, dive angle and heading) account for 57% of the total miss distance at 450 knots and 40% at 860 knots (the overall effect of errors in aircraft release conditions is less sensitive at higher speeds). On the other hand, those parameters relating to the store itself (store weight, diameter, drag coefficient, and inertia) account for only 10% of the total miss distance at 450 knots but 31% at 860 knots. This emphasizes the need to maintain store mass properties within allowable tolerances, and the smaller the tolerance the better. Lastly, those parameters due to store separation from the aircraft (variation in ejector end of stroke velocity, pitch rate, and store pitch and yaw) account for 30% of the total miss distance at 450 knots and 21% at 860 knots.

The authors interpretation of these figures is that store separation from the aircraft itself plays a part, but a small part, in the overall miss distance. The store separation engineer can attempt to minimize ballistic errors due to ejector pitch rate, but the store separation engineer has no control on mass properties of stores used operationally or in errors in flight conditions at stores release.

The results of analyses such as the above are clearly quite valuable in structuring a flight test program because it provides the store separation engineer with hard data upon which to make decisions as to whether or not it is worthwhile to perform additional testing to "fine-tune" ejector performance and other parameters. For example, Table V also presents data for the same store released at 800 feet (above ground level) in a 45 degree dive at 450 knots and 860 knots. At this condition, parameters relating to stores release account for 40% of the total miss distance. Because this value is substantial, it may well be worthwhile to "fine tune" ejector performance to minimize store perturbations at release under these conditions.

The authors have uncovered little information on how various organizations actually perform ballistic delivery and analyses. As a result, Appendix E was prepared especially for this report. It summarizes the approach and methods used in the USAF for performing this type of work. It is hoped that this information will be of assistance to the reader.

9.0 FUTURE TRENOS

By this time, it should be apparent to the reader that store separation is a serious problem-one which requires the careful attention of dedicated, experienced engineers, and the application of continuously evolving state-of-the-art technology and sophisticated testing techniques. Because it is a problem with life-or-death implications for the aircraft flight crews, it must be given the most intense scrutiny by all organizations involved, both by the testing and evaluation community who determines the acceptable store separation limitations, and by the operational community who must operate within these limits and who must know the consequences of exceeding them.

Store separation is largely an aerodynamics driven problem. Although the majority of problems occur at high speeds (usually high subsonic or transonic), severe problems may also occur at relatively modest airspeeds. For example, the severe problems discussed earlier that occur on the A-10 aircraft at 350 KCAS are due primarily to its very thick high camber airfoil wing, which reaches critical Mach at around 0.6M. Store separation problems are also exacerbated by such things as flexible, multiple bomb racks, high winged aircraft, close spacing between pylons or stores, and local aircraft flowfield irregularities. Ironically, the worst problems have occurred on US aircraft, caused primarily by a method of store carriage largely designed by US engineers; flexible multiple bomb ejector racks. In the late 1950s and early 1960s, US political and strategic policies shifted from a nuclear strike role to one of flexible response, including emphasis on the delivery of conventional stores. Almost immediately, a crash effort was made to equip the already existing USAF and US Navy nuclear strike aircraft with the capability to carry and deliver large numbers of conventional stores, and the Multiple Ejector Rack (MER) was born. Because aircraft were now flying at much higher speeds than those used only a few years before, stores had to be ejected rather than gravity released. Little thought was given then to store separation. Over the years, US policy has kept the requirement for delivery of large numbers of conventional stores, while cost considerations have required that US tactical airc be multi-missioned, thus assuring that the aircraft be equipped with removable external pylons and multiple racks. In the past 20 years the stress on developing aircraft with the maximum clean or a to-air combat performance in the US has produced aircraft that are nothing short of marvelous. But this policy has also assured that air-to-ground store carriage techniques and equipment were never allowed to develop to their potential, and 1960s vintage Multiple Ejector Racks are still being used on the latest USAF and US Navy fighter and attack aircraft (usually with significant flight limitations). Fortunately, this situation in the US has begun to change. The store separation problems generated by the use of these flexible MERS have historically been primarily US only, since the other nations in NATO have generally retained the single carriage (one store per pylon) carriage concept. Recent years have been marked with the development in Europe of a few twin-store or multiple store ejector racks, but by and large, the European members of NATO have chosen the more simple and more aerodynamically clean store carriage methods, and this trend continues today and for the foreseeable future.

European engineers have not had to face, at least not on a routine basis, the complex store separation situations which bedevil their US counterparts. And now, fortunately for the US store separation engineers, US aircraft design policy has begun changing and rapidly so. The USAF recently announced to industry that all aircraft in the future will utilize some form of conformal carriage of stores. Even the aircraft in development today, the F-15E Dual Role Fighter and the F-16 with the cranked-arrow wing, will both employ the semi-conformal, or tangential, carriage method as shown in Figures 51 and 52 respectively. Also, the use of the existing multiple racks on existing USAF aircraft such as the A-10, F-4, A-7 and early model F-16s will be minimized with the emphasis on one store per pylon. The US Navy has not yet followed suit, primarily because of aircraft carrier operations requirements and the need to rapidly reconfigure aircraft from air-to-air to air-to-ground and vice versa. However, the use of conformal carriage for new US Navy store-carrying aircraft now on the drawing boards is being seriously considered.

With the development of conformal carriage and new bomb Ejector Release Units (ERUs) with such features as automatic sway braces, better ejection forces and built-in store pitch control, stores may now be rapidly loaded one at a time on an aircraft and then safely carried and released throughout a large part of the aircraft's achievable flight envelope. Conversely, flexible multiple bomb racks with stores ejected both vertically and slanted, have historically severely limited the allowable store separation envelope. Figure 53 shows the allowable flight envelope for an F-4 aircraft loaded with 12 MK-82 500lb bombs. On the left is the envelope allowed when the bombs are carried on existing multiple racks, and on the right the envelope when conformal carriage is use. The contrast is striking. Incidentially, the data contained in this figure came from an actual joint flight test performed in 1973 by the US Navy and USAF in which a pallet containing 12 ERUs was attached to the F-4 fuselage which allowed 12 stores to be carried in a conformal array of four stores across three in each row. Although this was a highly successful validation of the conformal carriage concept, it has taken another decade for these improvements to begin to emerge operationally.

Carriage of stores conformally contributes two significant improvements relative to store separation that are so significant they dominate all other effects. First, the stores are ejected vertically and the aircraft structure to which the stores are attached, and from which they must be ejected, is much more substantial structurally with little flexibility. This allows the application of more effective ejector forces. And second, the flowfield around stores carried conformally, whether on the fuselage or on the wing, is much more linear and unlikely to have the large perturbations so common when multiple racks are used, thus allowing safe separation over a much wider variation of conditions. Figure 54 demonstrates the clean separation of multiple bombs from an F16XL at 550 KCAS.

In spite of the above, the authors observe that, even for future aircraft, some designers are tending to try to stick to the old adage of "design the clean aircraft for optimum performance (or perhaps in an air-to-air configuration), and then hang the stores on wherever you can". Fortunately, most aircraft designers now recognize that the aircraft should be capable of operating with stores attached in almost the same maneuvering envelope as the clean aircraft. To do this, the stores carriage methodology and provisions <u>must</u> be designed into the aircraft from its inception. While some designers have opted for true conformal carriage of external stores (including the use of specially shaped blended-body stores), others have rediscovered internal carriage of stores. Bomb bays for tactical aircraft have been tried in the past, and in almost every case have not been effective. Not only is the internal space in a tactical aircraft very limited, but the shape of air-to-ground stores, with their fuzes and fins and other protuberances do not lend themselves to efficient internal-bay packaging. Last, but not least, an internal bay is at the very best only 50% efficient on each combat mission. After the stores have been expended, the aircraft must return to base with a large empty volume, which nevertheless still has the same drag as when it was full. In the US, the jury is still out on whether internal carriage will re-emerge. It may reappear only for the carriage of air-to-air stores on supersonic persistent fighter aircraft.

USAF design studies still show that the most efficient method of carriage for air-to-ground stores is external conformal carriage utilizing specially shaped blended-bodies. For this reason, it appears that, at least for future USAF aircraft, conformal carriage is the method most likely to emerge. USAF aircraft designers are currently designing their aircraft with large flat areas on the botton surface of the wing and/or fuselage. Stores designers are designing and testing blended-body shaped stores with a flat upper surface that are capable of being flush mounted on the aircraft. Store ejector units will be built in to the aircraft structure to allow flush mounting. USAF aircraft with this type of weapons carriage should emerge in the 1990's, as design efforts are already well underway. Although the authors cannot speak for the other services or nations, we are convinced that such designs will, for the first time since the initial emergence of the high-speed jet, put the emphasis on stores delivery and effectiveness rather than on store separation. This is a healthy trend; one which we hope will grow rapidly.

10.0 CONCLUSIONS

In conclusion, the authors hope that this report has succeeded in presenting new store separation engineers and managers with a valuable discussion and bibliography of the methods used for performing store separation analysis and flight testing. The authors have attempted to present some of the advantages and disadvantages of each method, and have tried to make the reader aware of the requirements and constraints affecting a store separation program that might influence the choice of these methods. There is not now, nor is there ever likely to be, any one method of either prediction or testing that is superior to all the other methods in every situation or case. Rather, there are a number of good, proven, methods and techniques available to the store separation engineer, and these must be meshed with particular requirements (including cost and time) to determine which method is best for one's individual situation.

The methods that are in use in Europe are modern, effective and are responsive to the specific constraints placed on the organizations engaged in store separation. The same is true of the methods used in the US. However, because of the sheer volume of store separation testing in the US, the urgency of the situation to certify stores on many aircraft quickly, and the use of multiple carriage racks, store prediciton and test methods used in the US have not been the same as those chosen in Europe. While the US over the years has relied heavily on empirical, wind tunnel, or "brute force" techniques, the Europeans have placed more emphasis on analytical or theoretical methods. Analytical methods, even today, are most accurate and reliable when used in simple situations of one store per pylon, and with stores of relatively simple geometric shape. Although remarkable improvements have recently been made (both in the US and in Europe) in the ability of analytical techniques to handle complex store shapes and configurations, it will be years, in the authors' opinion, before such techniques will be capable of handling complex stores carried on several closely spaced multiple racks, and they may never be able to handle large numbers of stores released simultaneously, or in rapid ripple sequence. The trend in the USAF towards conformal carriage will, no doubt, have some effect on bringing the methods closer together. But, for the foreseeable future, the need to perform many tests in the shortest time possible (at the minimum possible cost) will dictate that the US continue to emphasize wind tunnel prediction methods (primarily grid and CTS), along with a judicious blend of "brute force" flight testing.

Table I - Store Separation Training Syllabus Outline

Forward

Purpose/Objectives

Lessons

I. Store Separation as a Discipline - Introduction

II. Getting Situated in the Work Environment

III. Aerodynamics and Kinematics of Stores Release

IV. Aircraft, Stores, and Racks

V. The Local Computer

VI. Wind Tunnel Testing

VII. Store Trajectory Computer Simulation/Analysis

VIII. Additional Analysis Aids/Computer Programs

IX. The Aero Memo - Technical Report

X. The Flight Test Recommendation - Flight Testing

Table II - USAF OAC In-House Compatibility Analysis and Test Capabilities

	A-7	A-10	B-1B	F-4	F-15	F-16	F-111
Compatibility Engineering	X	X	X	X	X	X	X
A/C Loads	X	X		X	X	X	X
A/C Stability and Control	X	X		X	X	X	X
A/C Flutter	Analogy	X		X	X	X	Analogy
EMC	X	X		X	X	X	X
Store Separation	X	X		X	X	X	X
Store Loads	X	X	X	X	X	X	X
Store Vibration	X	X	X	X	X	X	X
Wind Tunnel Test	X	X	X	X	X	X	X
Store Load Test	X	X	X	X	X	X	X
Aircraft Ground Vibration Test	X	X		X	X	X	X

X - Full Capability

TABLE III - AIRCRAFT/STORES CERTIFICATION FLOW CHART

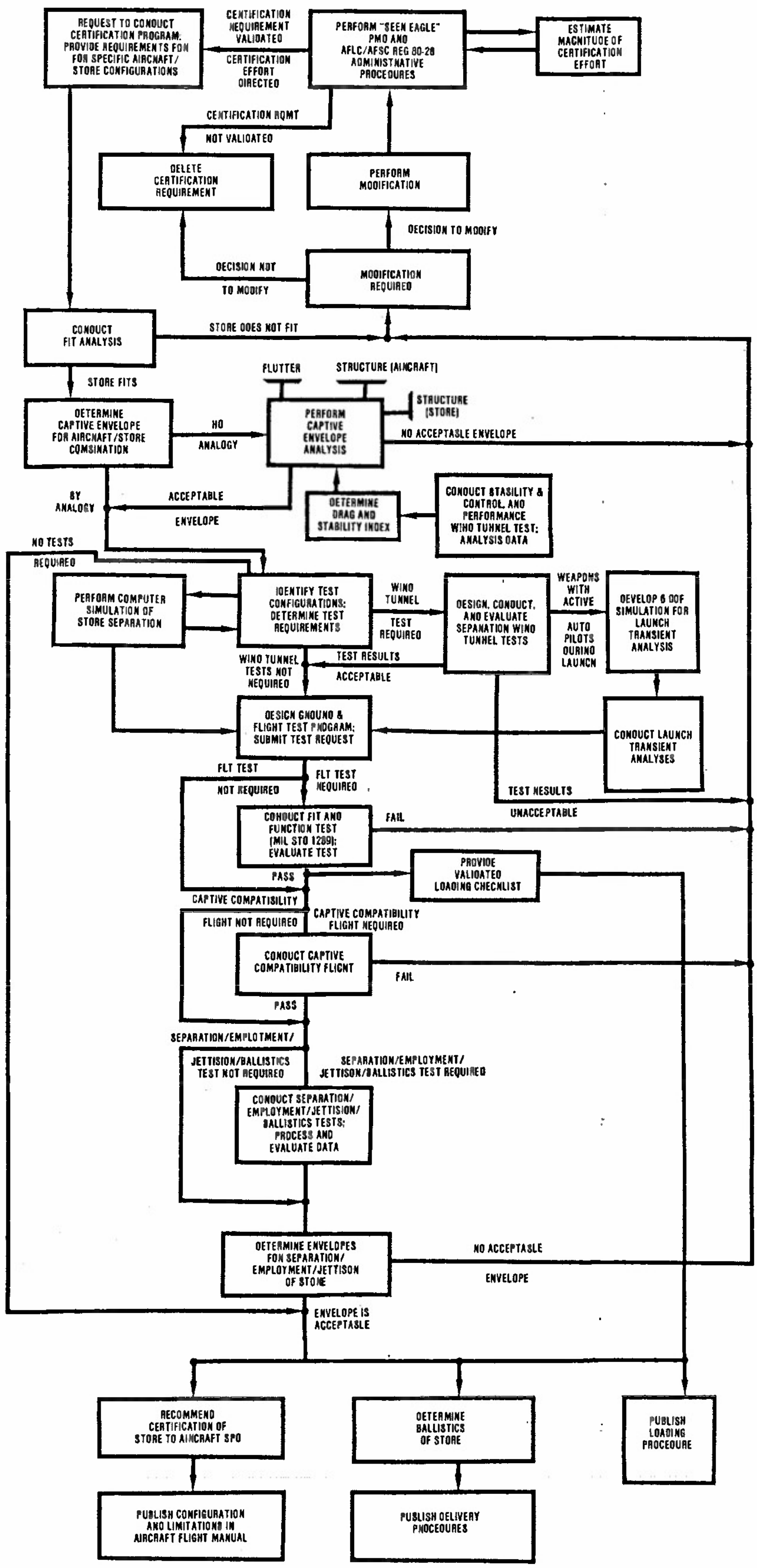
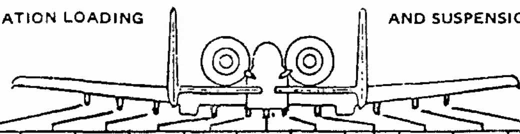


Table IV - Excerpt from A-10 Aircraft/Store Master Configuration List

MASTER CONFIGURATION LIST — STATION LOADING AND SUSPENSION — A-10 AIRCRAFT



LINE NO.	C.R. NO.	STORE TYPE	1	2	3	4	5	6	7	8	9	10	11	CARRIAGE KCAS/ MACH	CARRIAGE "G" SYM	EMPLOYMENT KCAS/ MACH	EMPLOYMENT "G" SYM	STATUS
13	7-84	AIM-9L/M on SMU												450 .75	7.3 to -3.0	450 .75	7.3 to -0.5	Awaiting EOP on SMU
14	12-84	LAU-131												450 .75	7.3 to -3.0	420 .75	4.0 to 0.5	Test Plan in Oraft
15	"	LAU-131 on TER-9A												450 .75	5.0 to -2.0	420 .75	4.0 to .0.5	"
16	13-84	ALQ-131 Band 4/5 Update												450 .75	7.3 to -3.0	NA	NA	Awaiting EDP
17	17-84	MJU-1A,B or M-129E1,E2												450 .75	5.0 to -2.0	420 .75	3.0 to 0.5	Test Plan in Draft
18	"	MJU-1A,B or M-129E1, E2 on TER-9A												450 .75	5.0 to -2.0	420 .75	3.0 to 0.5	"
19	8-85	AIM-9L/M OTM												450 .75	7.3 to -3.0	NA	NA	Awaiting EDP certify by analogy
20	9-85	ALQ-119-15/-17												450 .75	7.3 to -3.0	NA	NA	Awaiting EOP
21	10-85	ALQ-184(v)-1,-2												450 .75	7.3 to -3.0	NA	NA	"
22	12-85	BOU-50/8 Slick (LD)												450 .75	7.3 to -3.0	420 .75	3.0 to 0.5	Need to verify properties
23	"	BDU-50/8(LO) on TER-9A												450 .75	5.0 to -2.0	420 .75	3.0 to 0.5	"

Table V - Miss Distance of MK-82 Bombs Due to Various Parameters

Flight Condition	PARAMETERS: 50' Altitude Error	10 KTAS Error	0.1° Dive Error	2 fps Eject Vel Error	20 # Bomb Wt Error	0.5" Bomb Dia Error	5% Air Density Error	5% C_D Error	0.2° Heading Error	50°/Sec Pitch Rate	-5° Pitch	5° Yaw	4 Slug ft^2 I_o Error	Total-All Added
Level														
5,000 ft														
450 KTAS	76	155	41	44	7	20	11	12	45	61	36	9	14	501
860 KTAS	117	130	127	68	67	170	90	90	80	68	83	19	14	1,113
45° Dive														
8,000 ft														
450 KTAS	33	25	5	24	2	3	2	3	29	25	18	1	4	175
860 KTAS	27	75	3	17	3	5	4	2	35	19	26	1	2	152

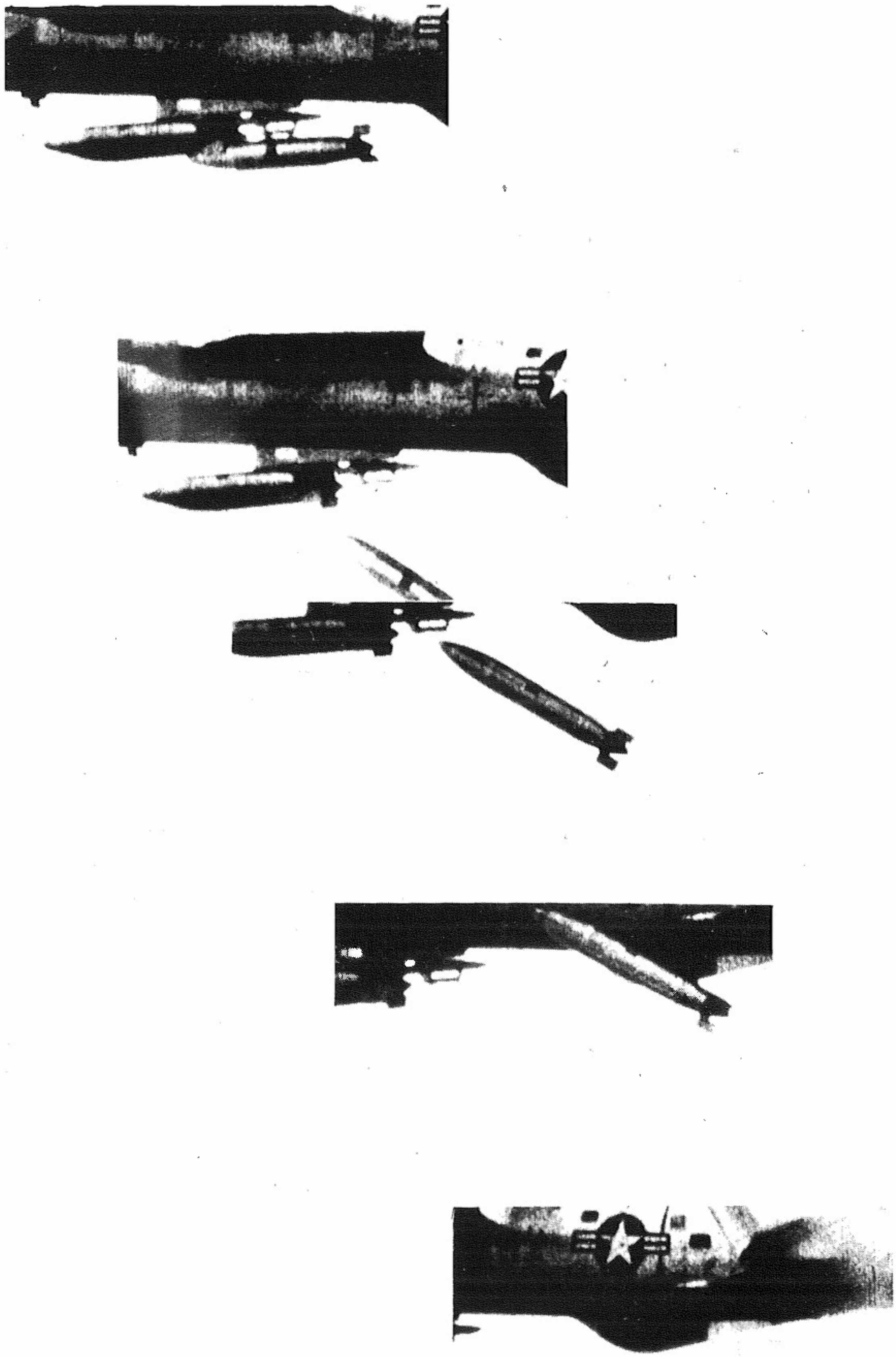


Figure 1 - Store to Aircraft Collision: BLU-1 Firebomb Released from F-105

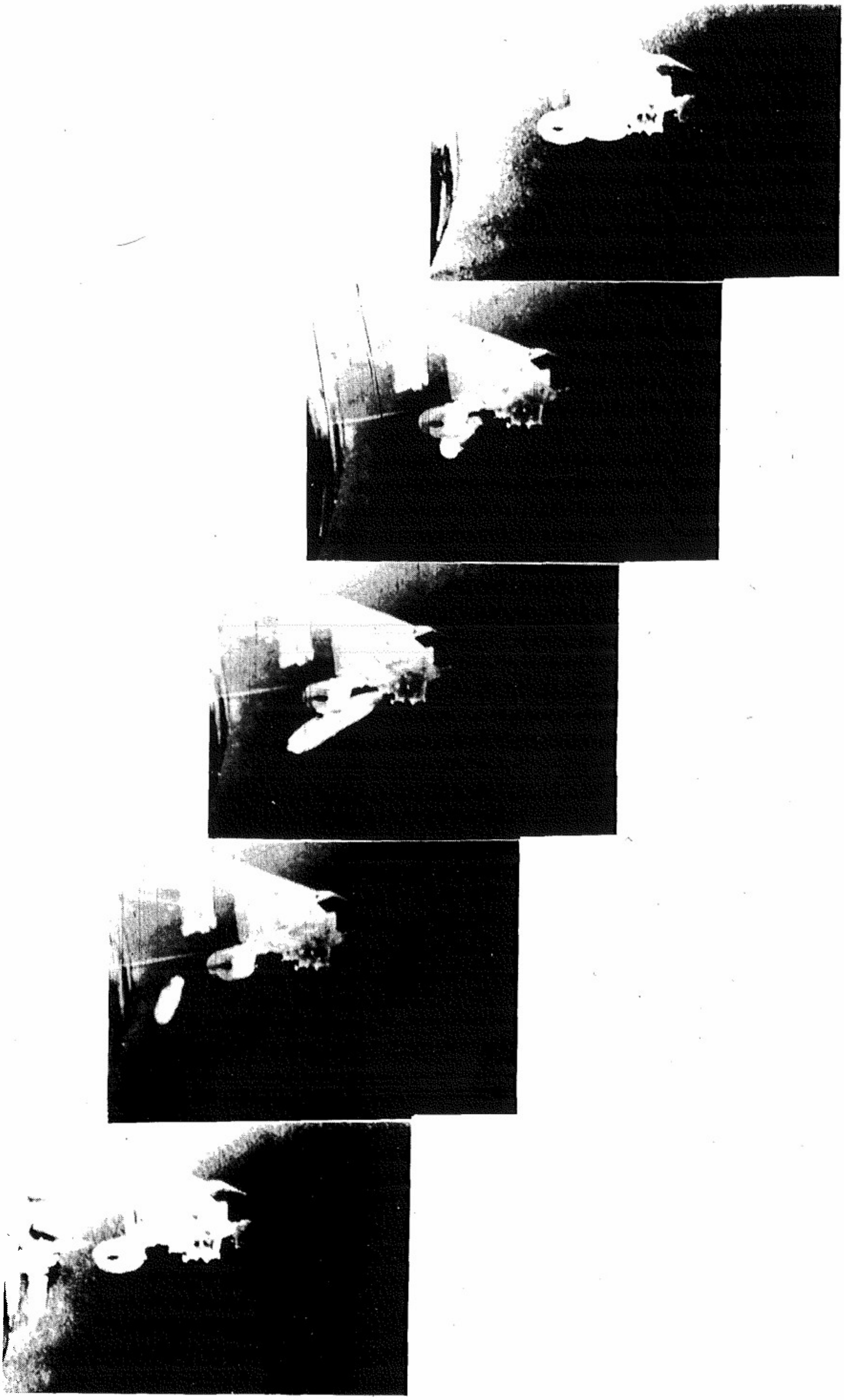


Figure 2 - Store to Aircraft Collision: MK-77 Firebomb Released from A-7 Aircraft

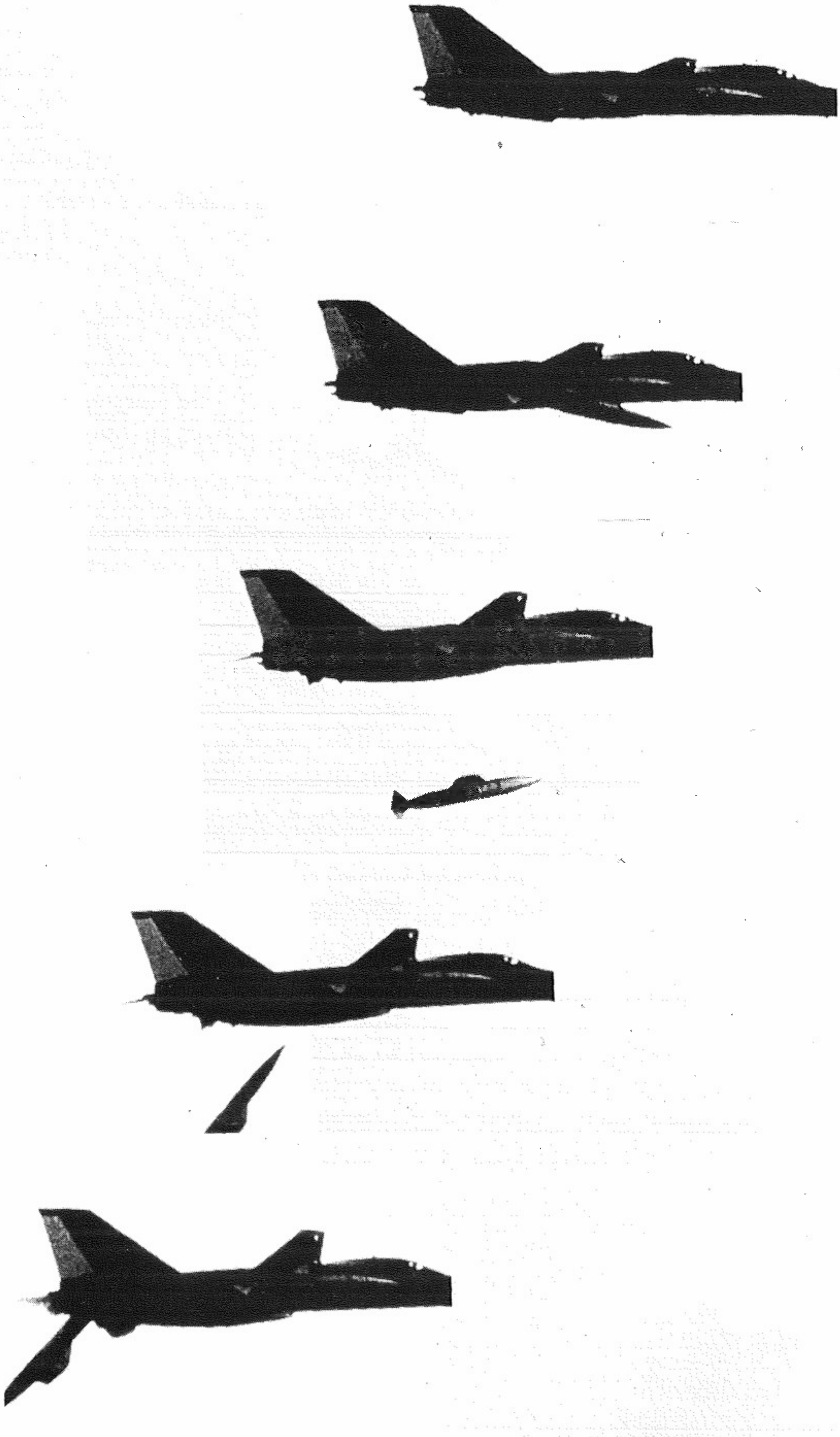


Figure 3 - Store to Aircraft Collision: Fuel Tank and Pylon Released from FB-111

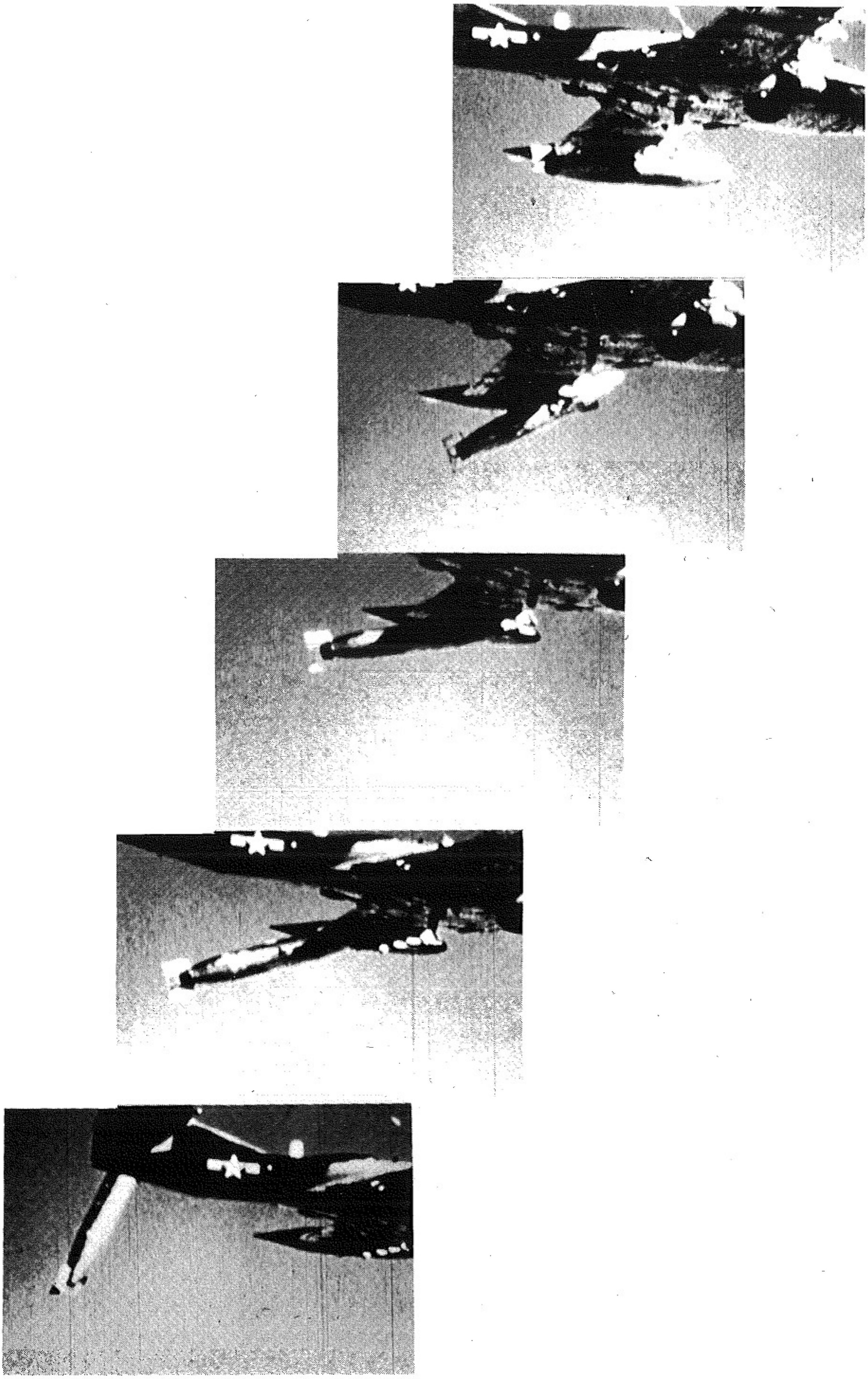


Figure 4 - Store to Aircraft Collision: Fuel Tank Released from A-37

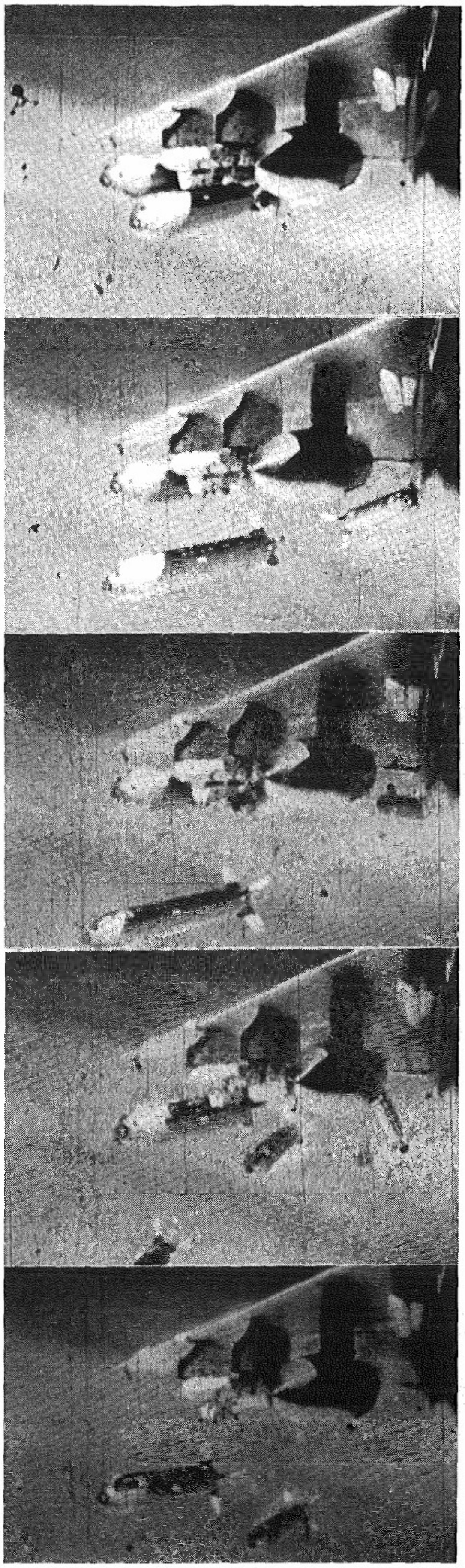


Figure 5 - Erratic MK-20 Rockeye Separation and Collision with A-7 Due to Uneven Fin Opening

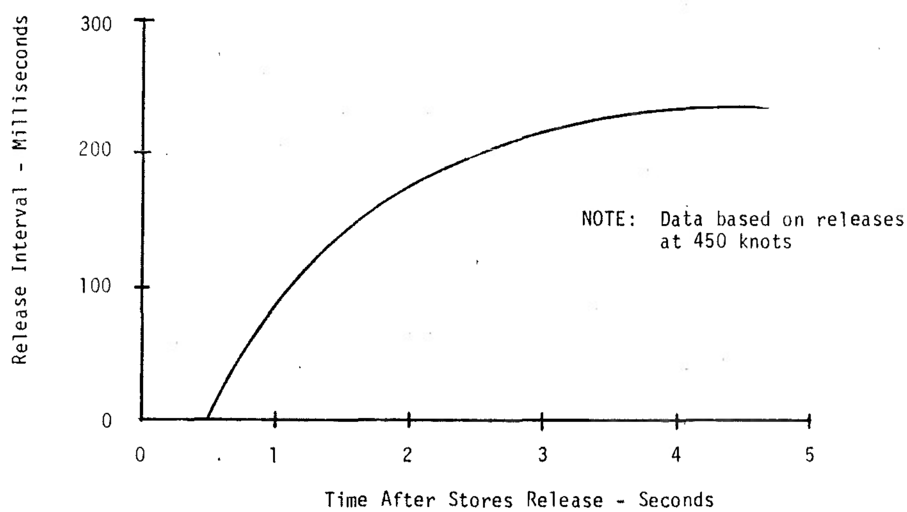


Figure 6 - Time for MK-82 Snakeye Bombs Released from Tandem MER-10 Stations to Collide

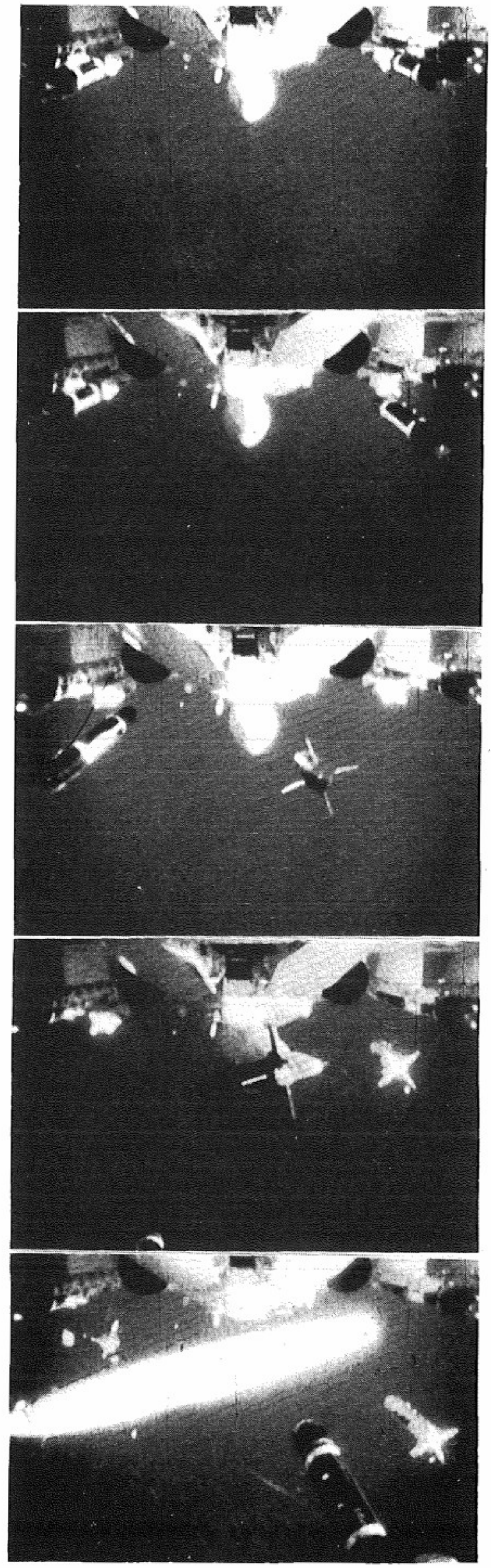


Figure 7 - Store to Store Collision: BLU-80 Stores Released from A-4

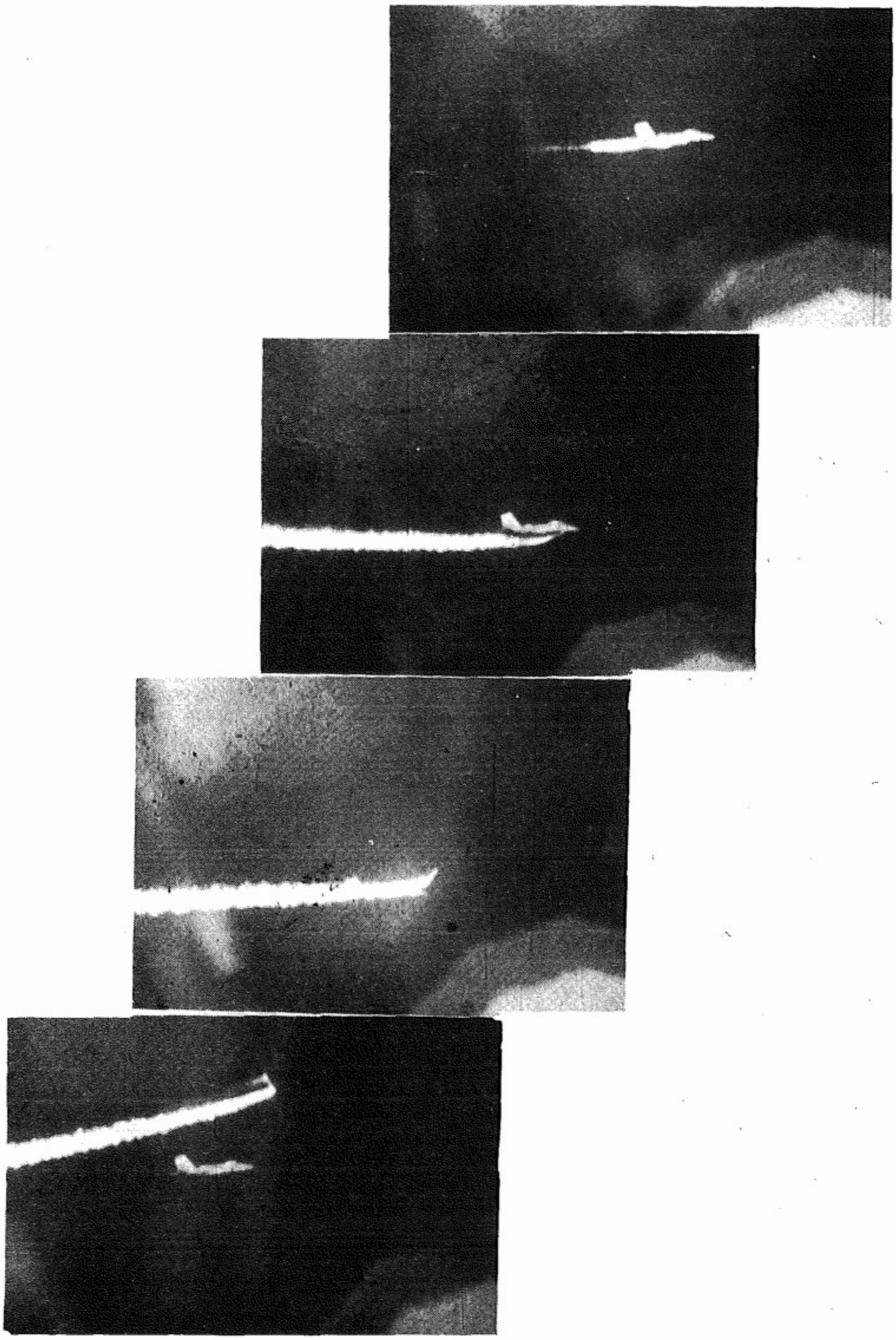


Figure 8 - Unsatisfactory Separation of AIM-7 Launched from F-15

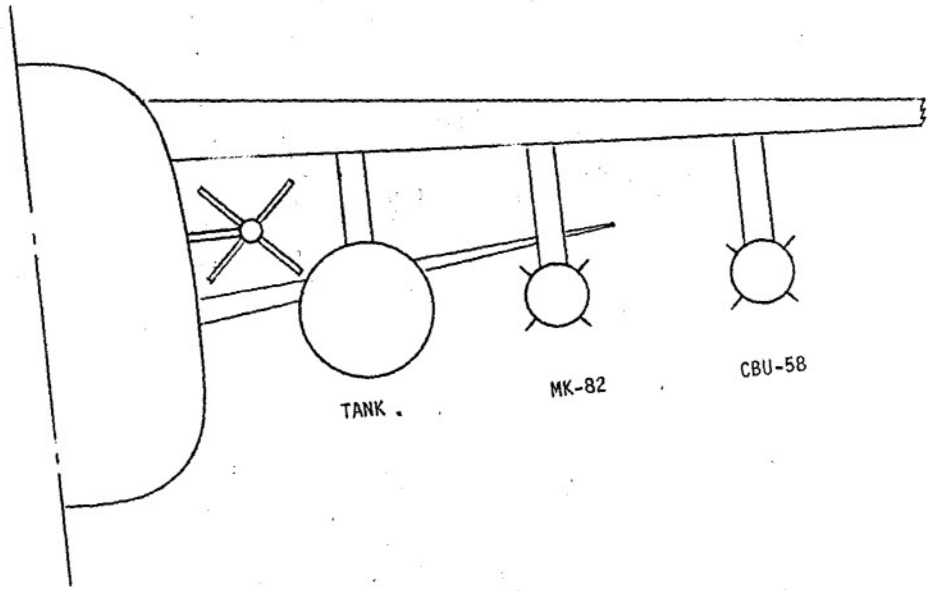


Figure 9 - Parent Pylon Carriage of Stores on A-7

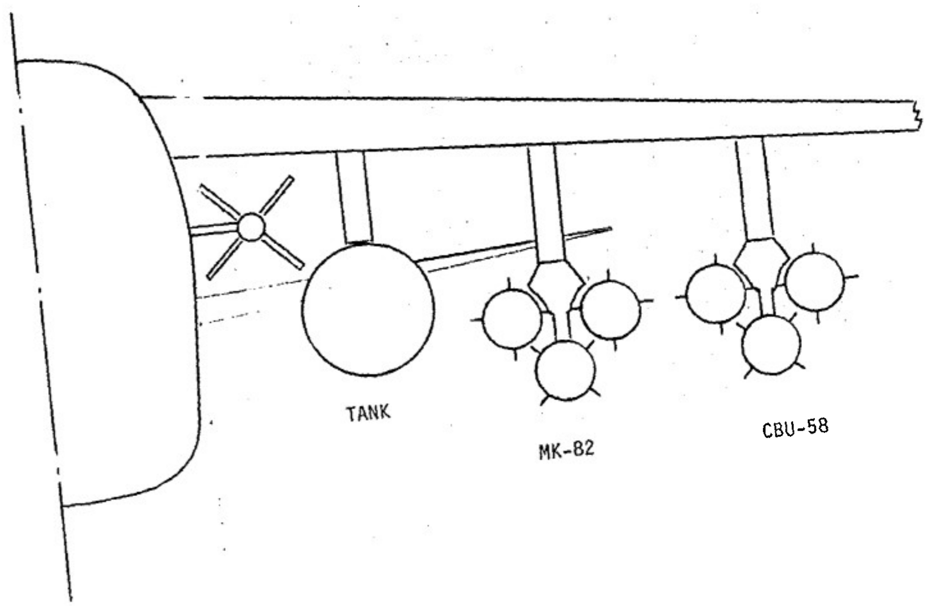


Figure 10 - Multiple Carriage of Stores on A-7

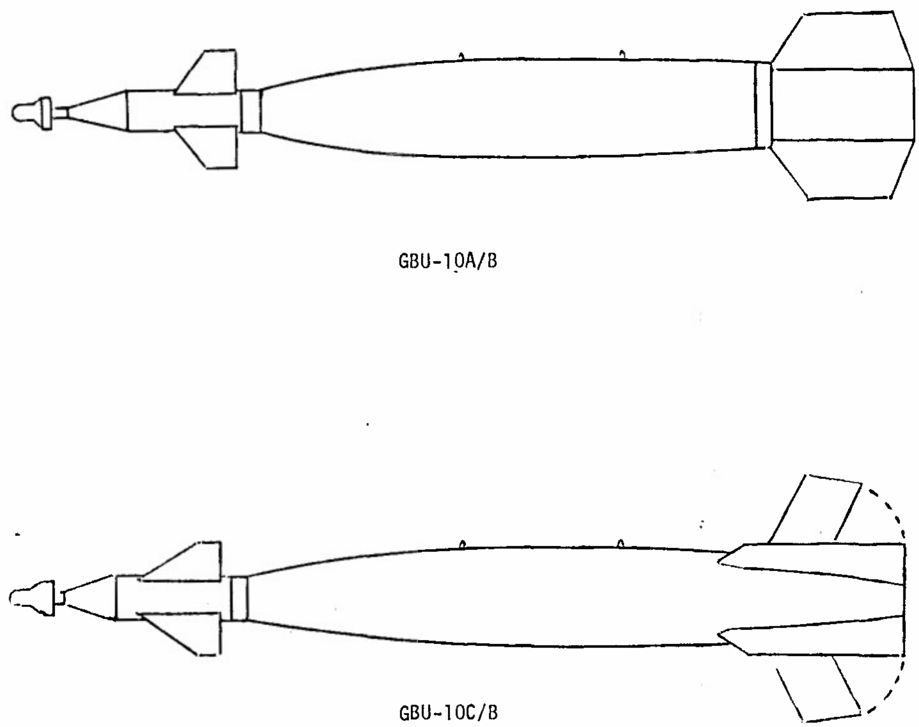


Figure 11 - Geometric Comparison of GBU-10A/B and GBU-10C/B Stores

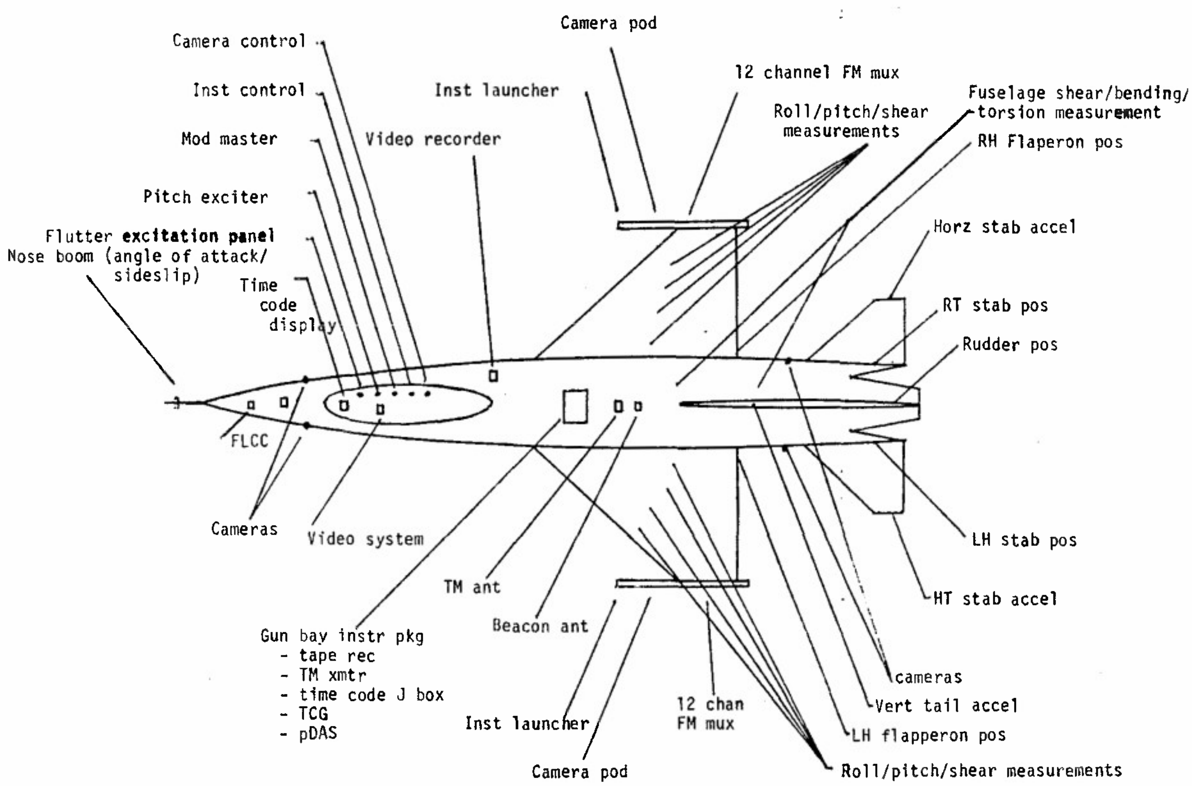


Figure 12 - F-16 Flutter and Loads Instrumentation

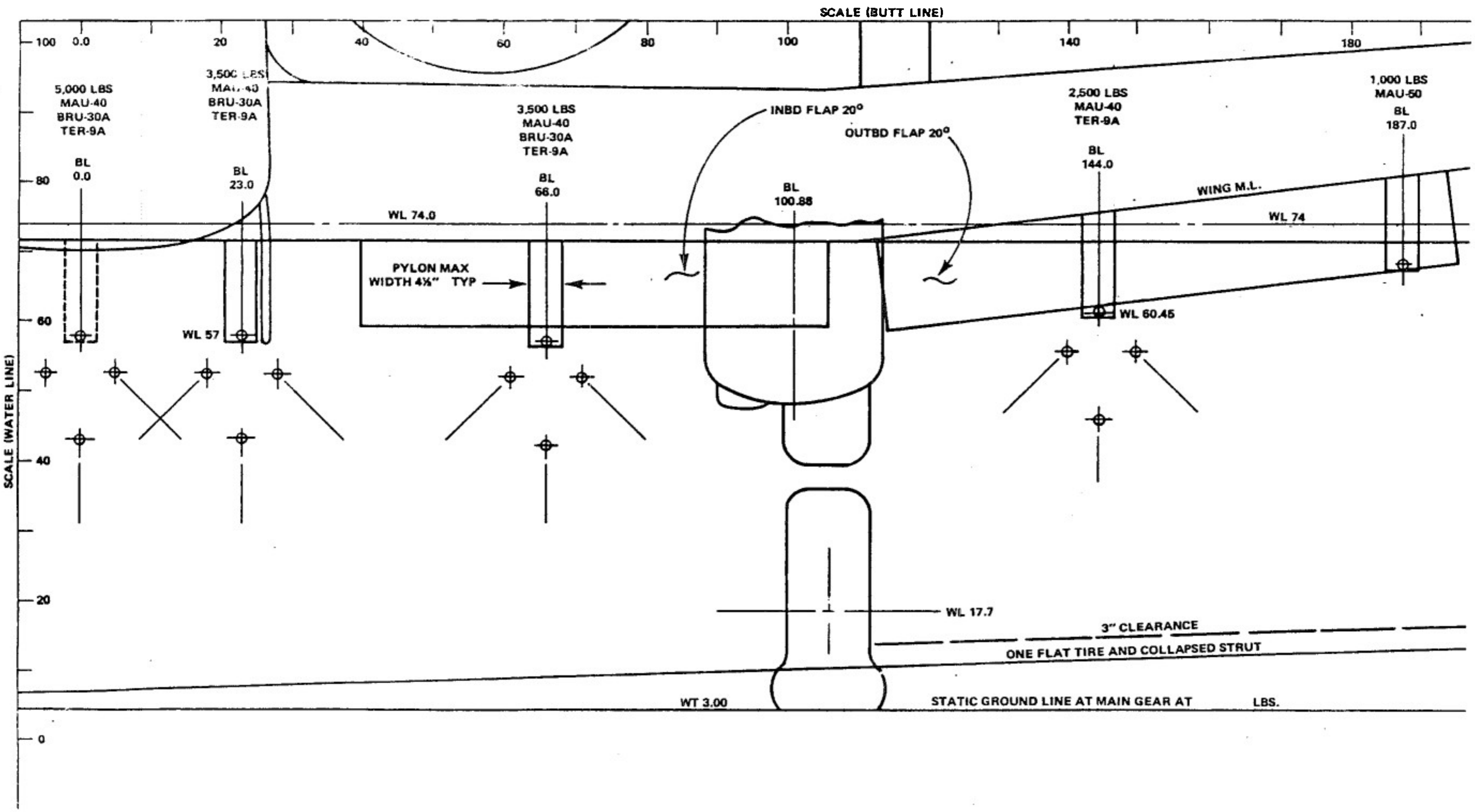


Figure 13A - A-10 ASIM Front View

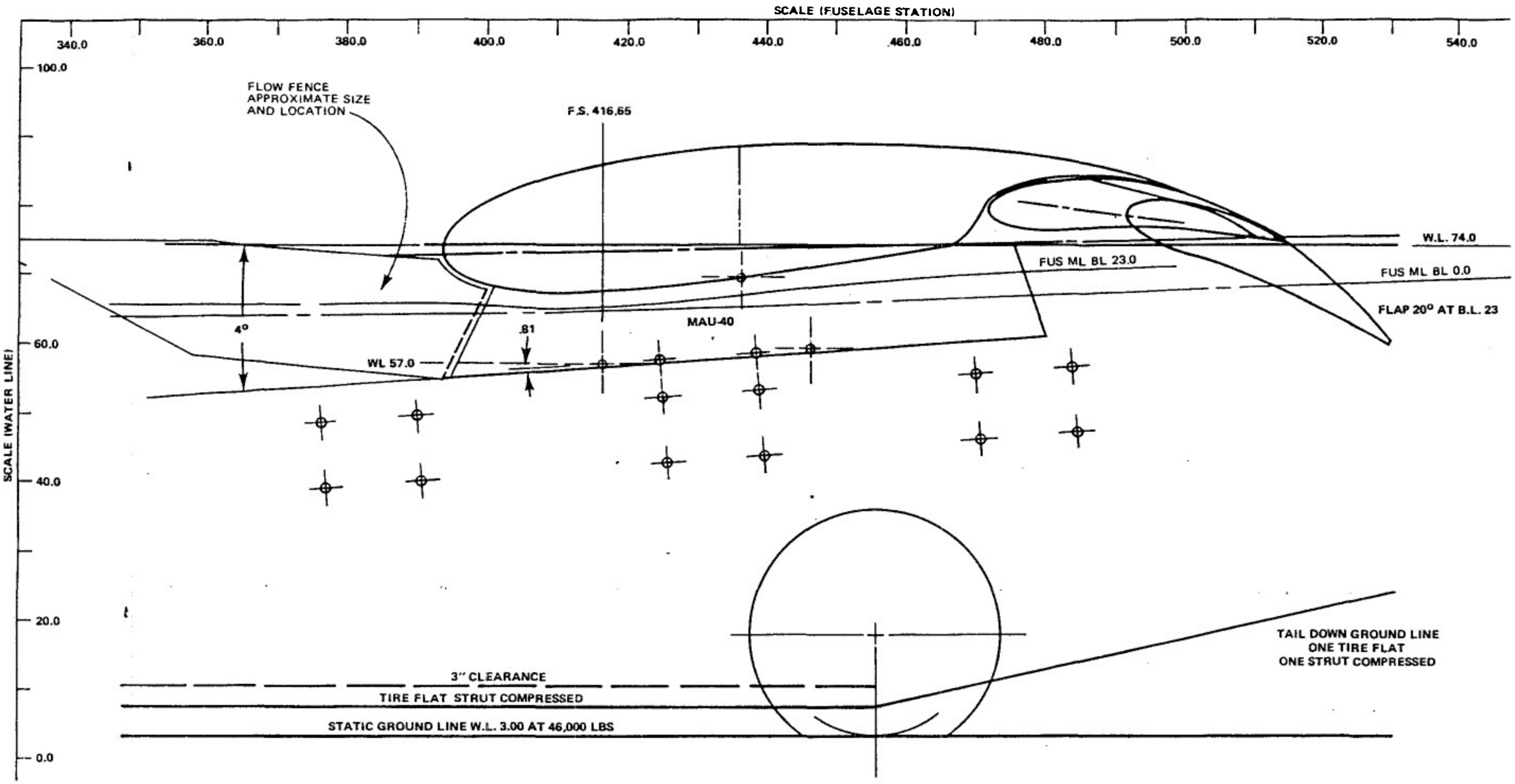


Figure 13B - A-10 ASIM Side View

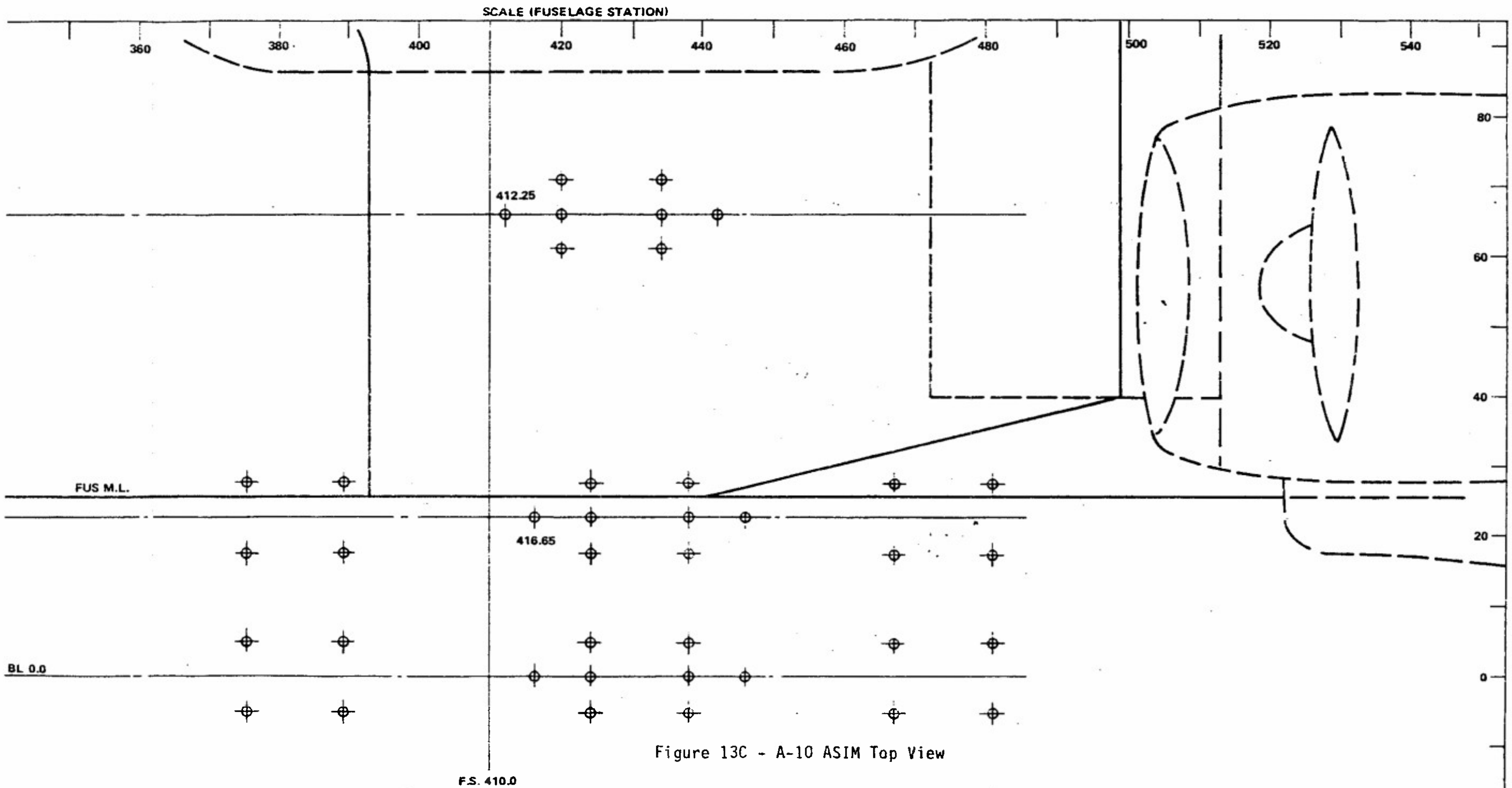


Figure 13C - A-10 ASIM Top View

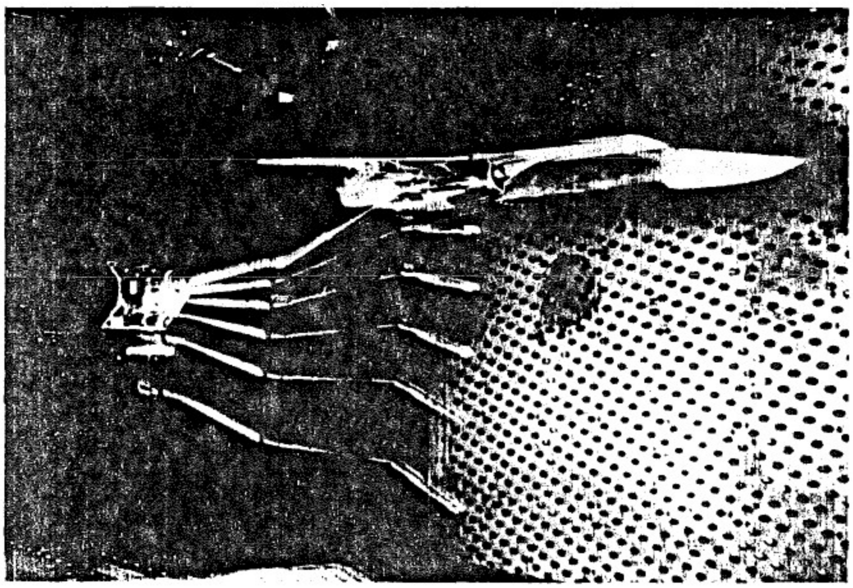
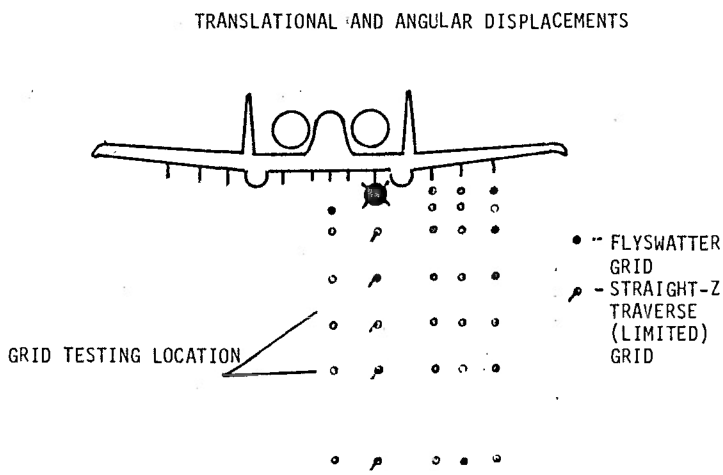


Figure 14 - F-111 Aircraft Model Installed on Captive Trajectory Rig in AEDC Wind Tunnel



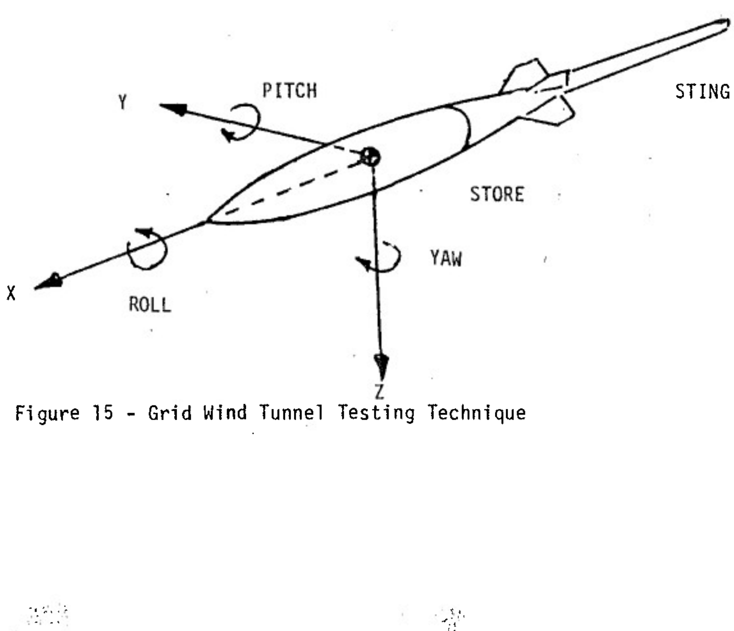


Figure 15 - Grid Wind Tunnel Testing Technique

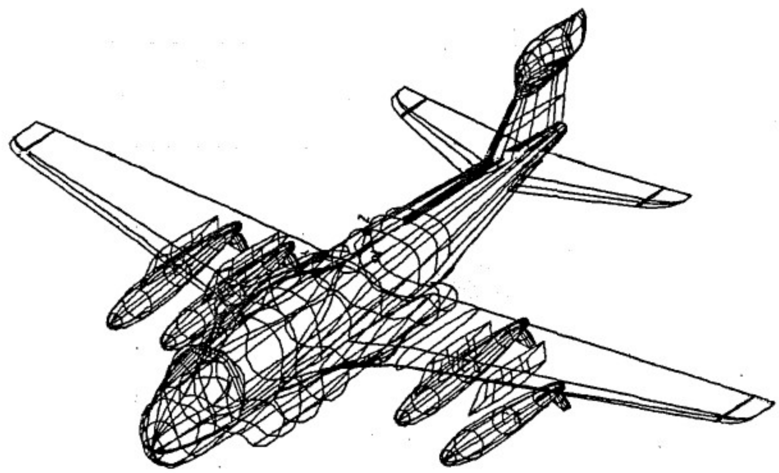


Figure 16A - Enhanced Computer Graphics Depiction of Predicted Store Separation Characteristics: Three Quarter View

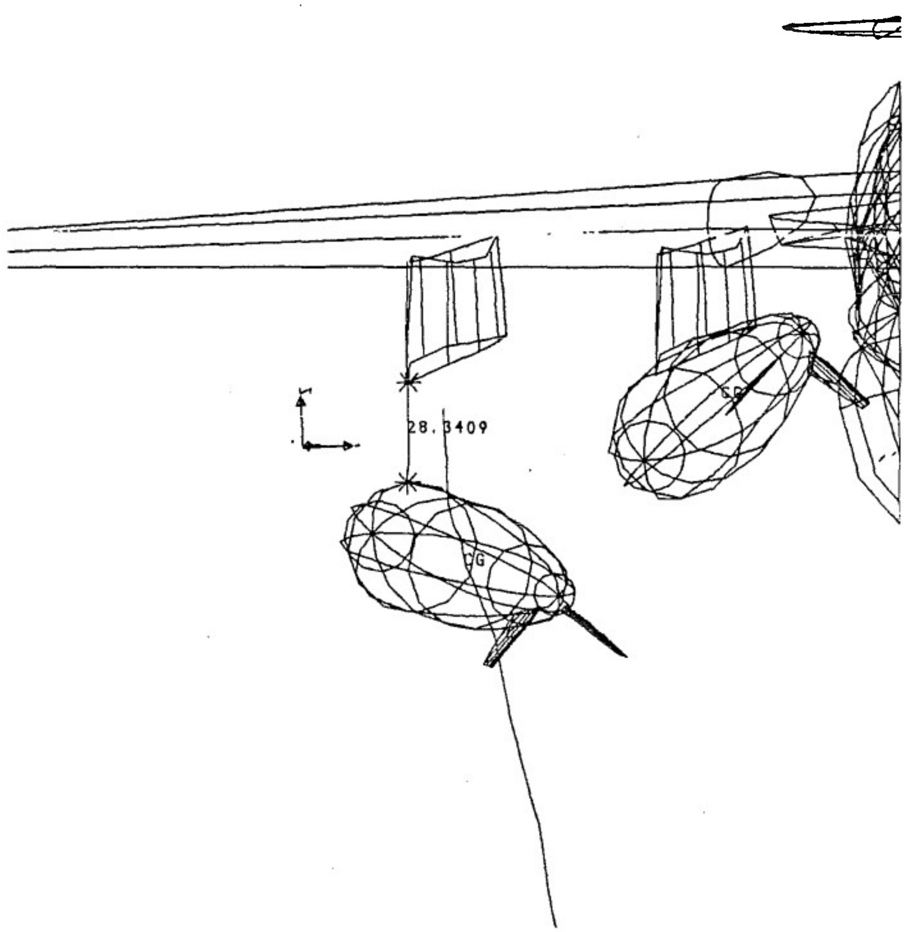


Figure 16B - Enhanced Computer Graphics Depiction of Predicted Store Separation Characteristics: Rear View

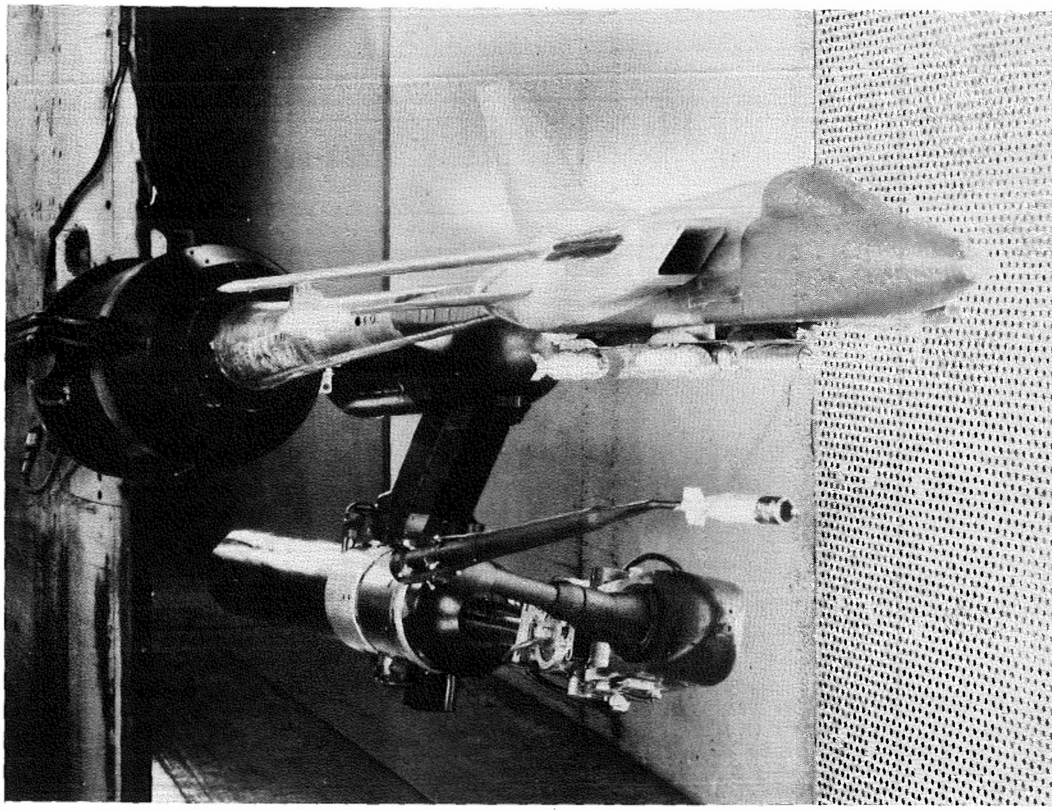


Figure 17 - Tornado Model Installed on Two Sting Rig in ARA Wind Tunnel

Figure 18 - Fuel Tank Mounted in Displaced Position on NLR
Captive Store Load Measuring System on NF-5

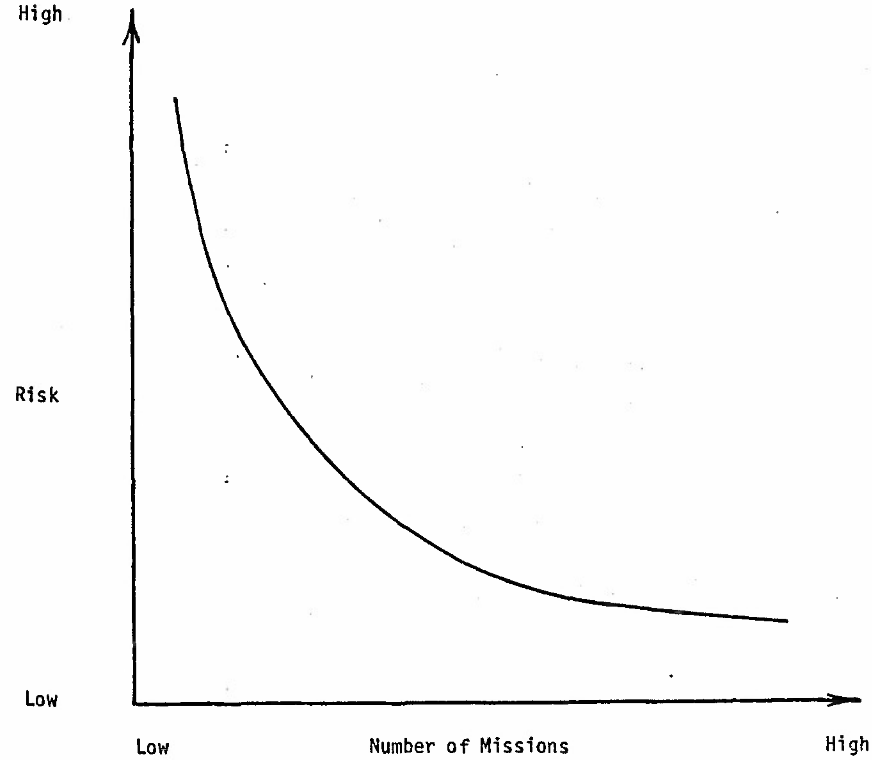


Figure 19 - Risk as a Function of Missions

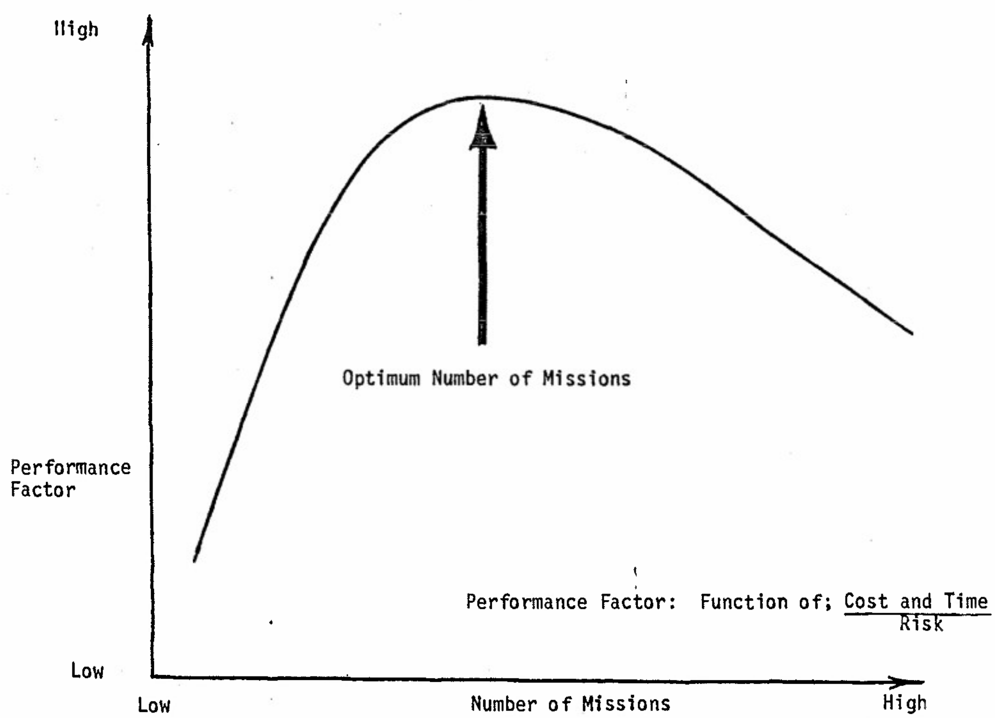


Figure 20 - Performance Factor as a Function of Missions

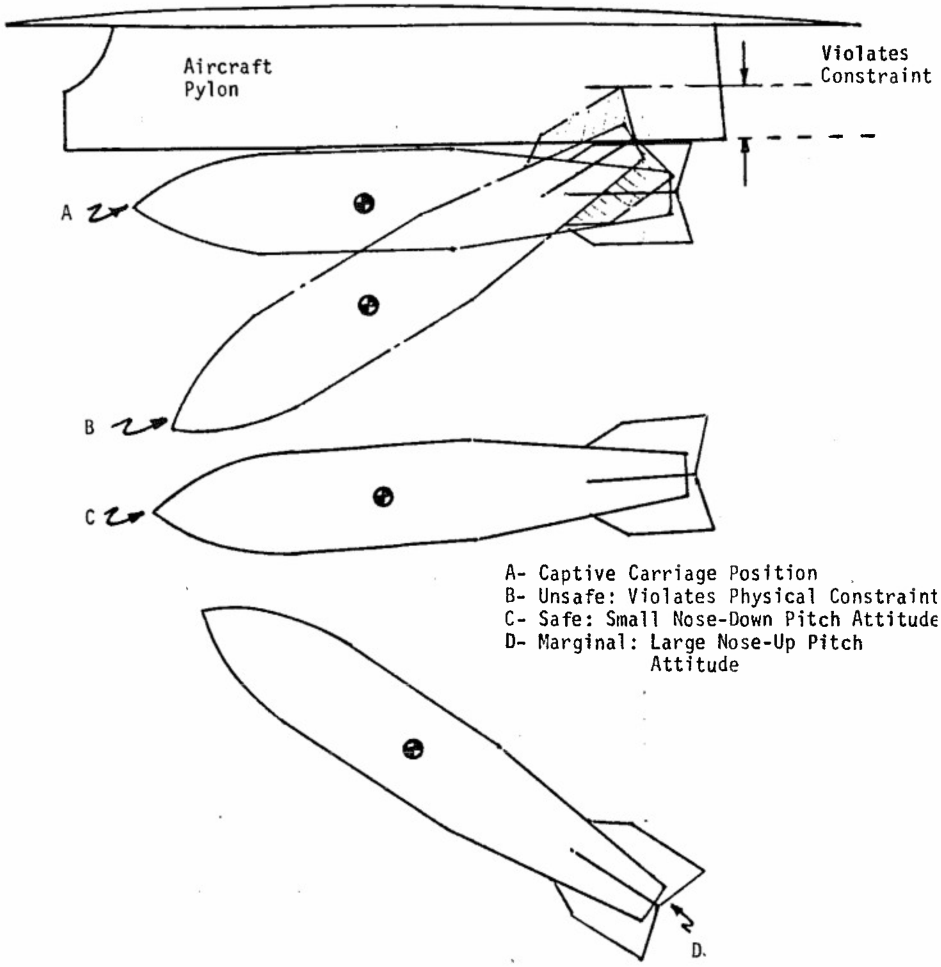


Figure 21 - Captive Carriage Store Separation Constraint

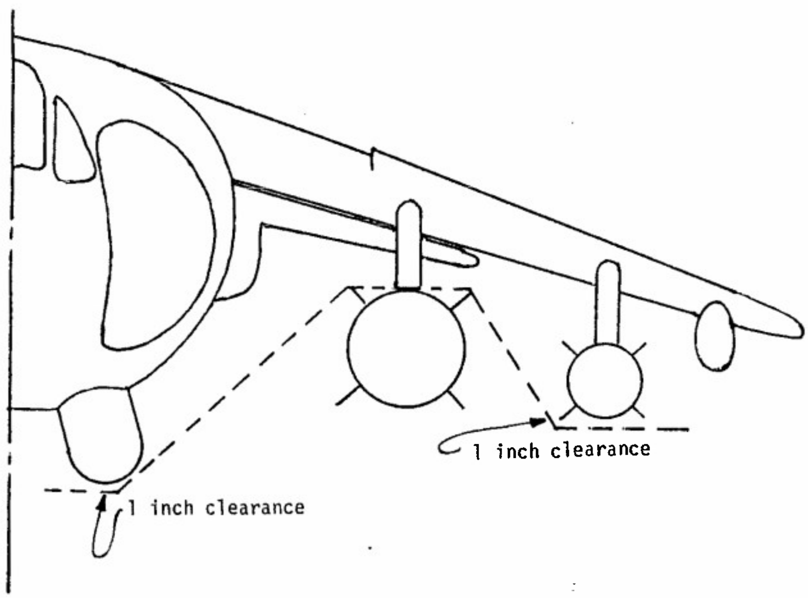


Figure 22 - Illustration of Typical Captive Carriage Store Constraint

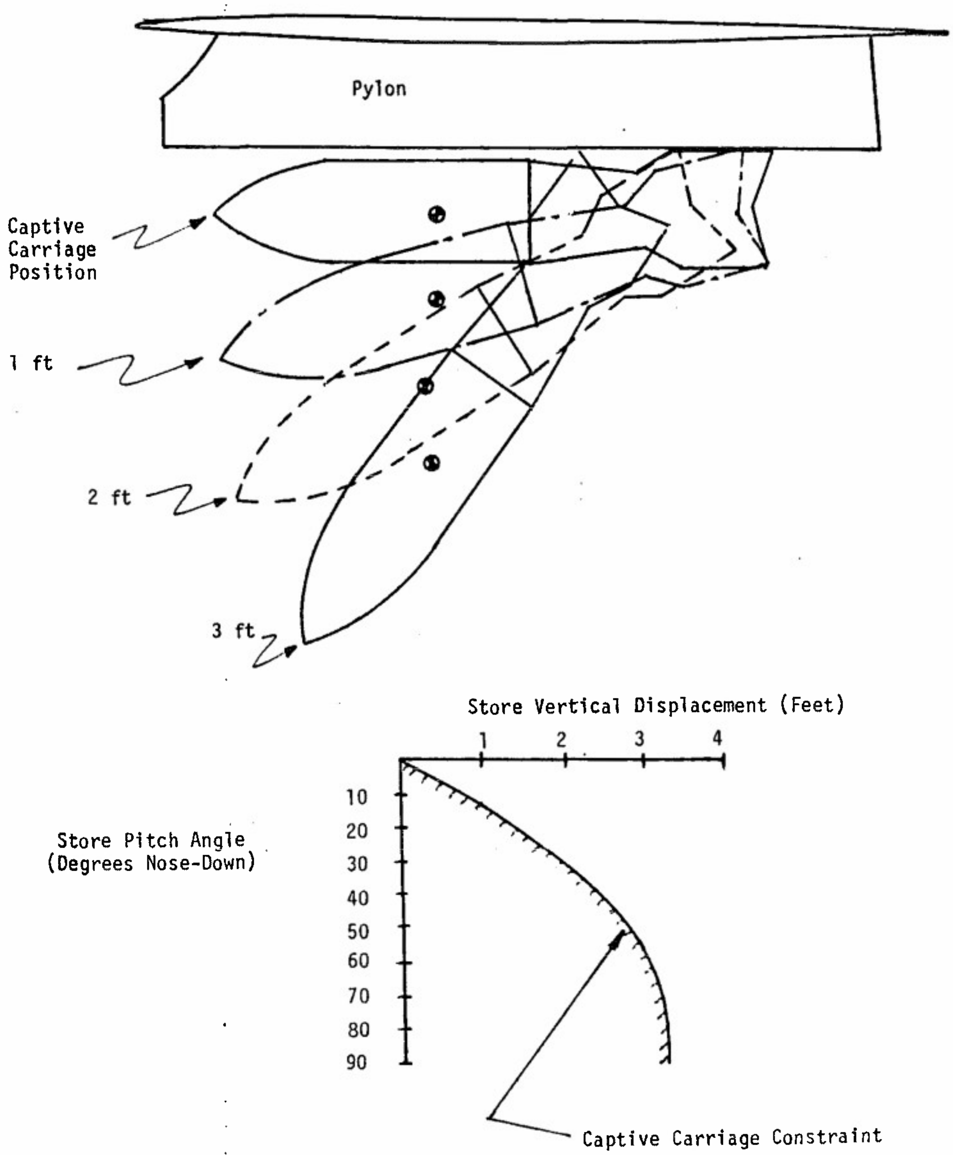


Figure 23 - Development of Captive Carriage Store Constraint

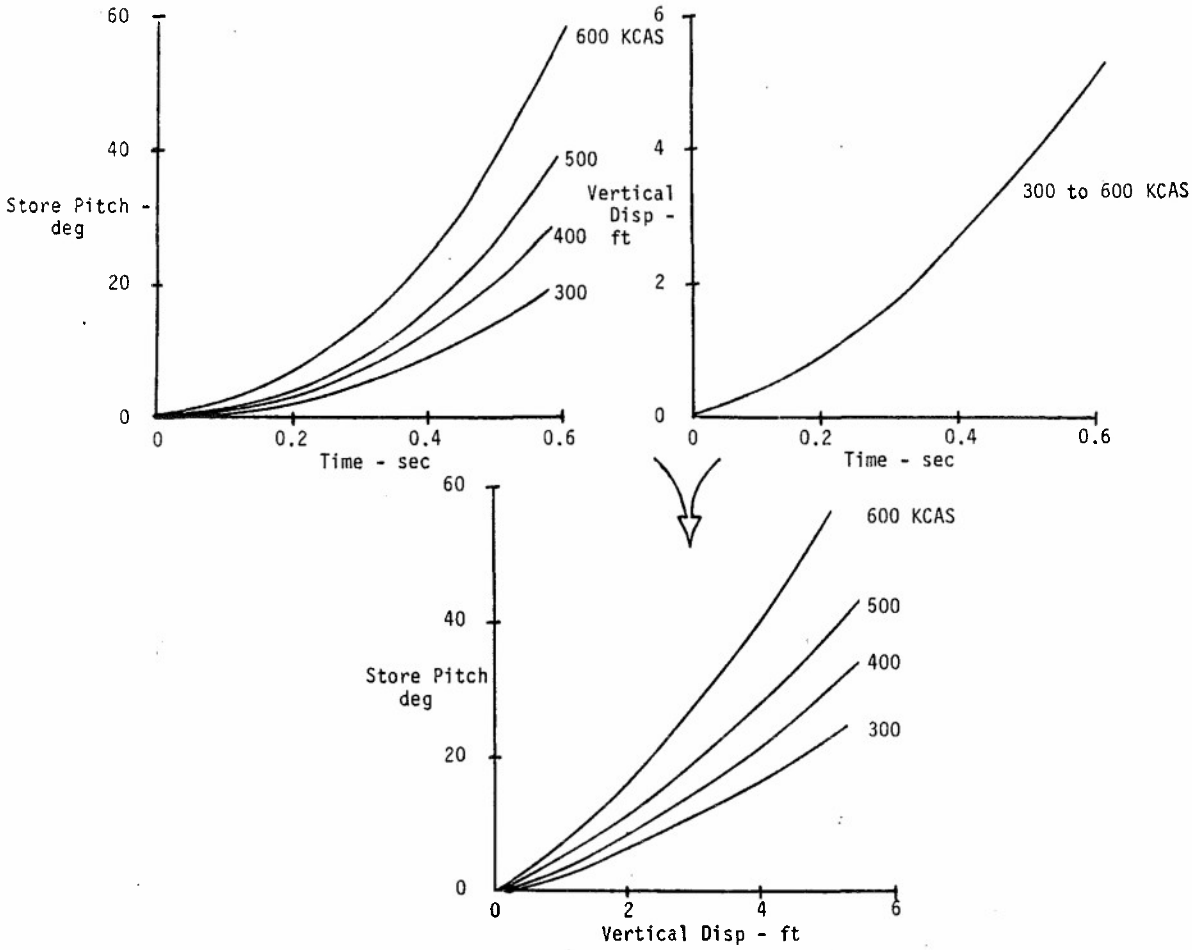


Figure 24 - Development of Store Collision Boundary: Store Pitch Versus Vertical Displacement

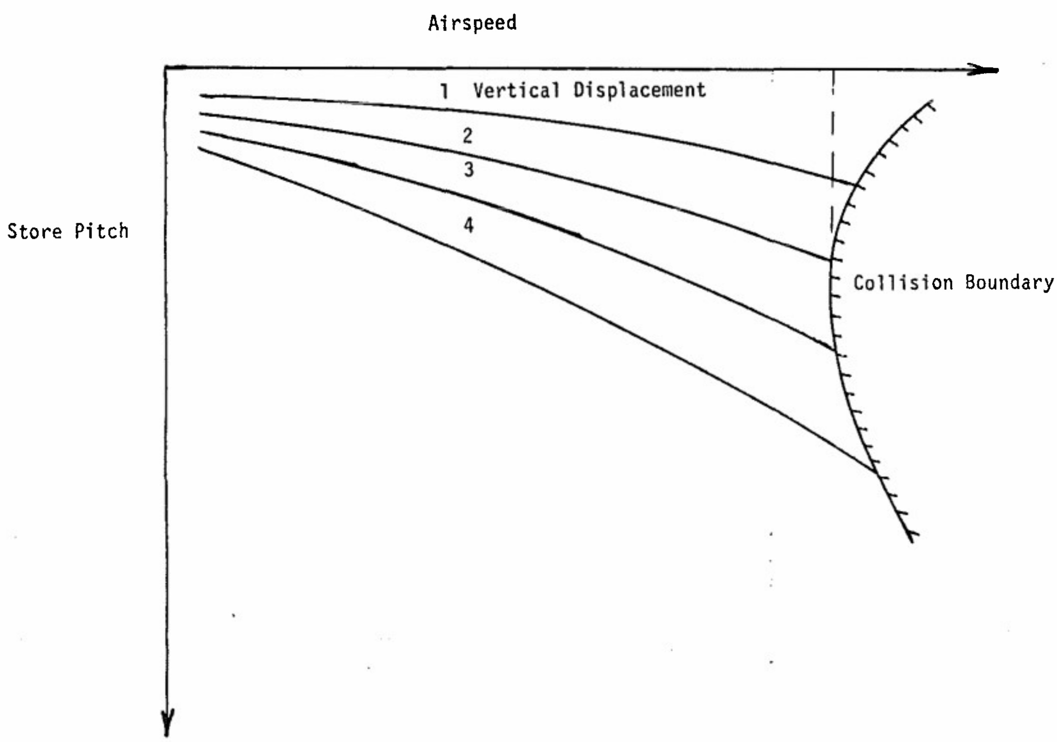


Figure 25 - Store Collison Boundary Plot: Smooth Speed Continuity

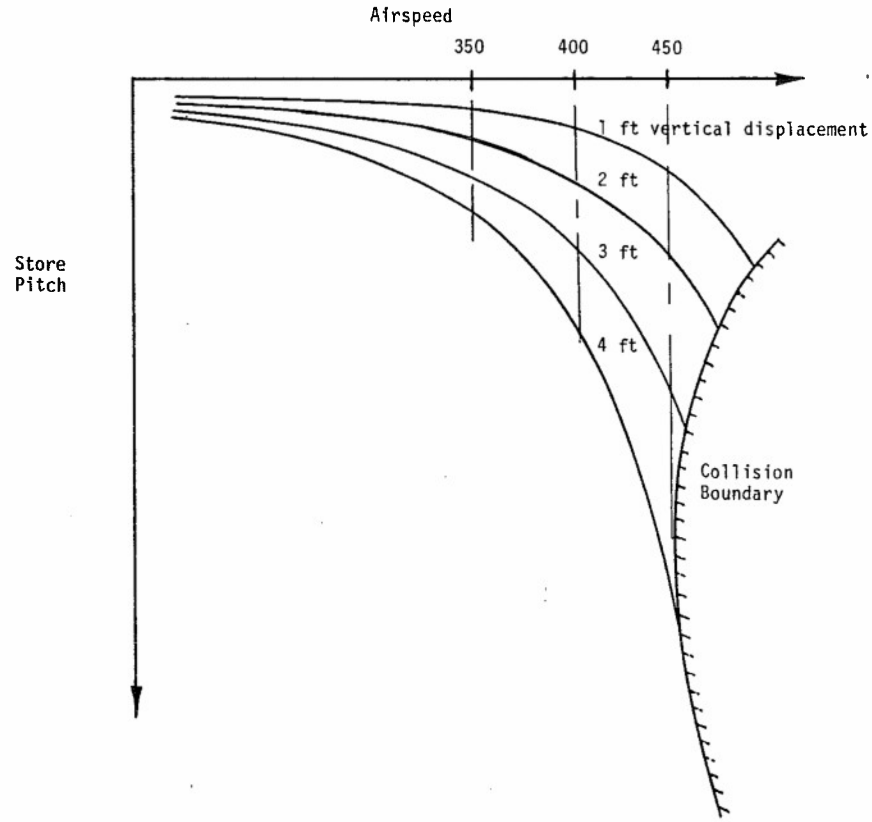


Figure 26 - Store Collision Boundary: Abrupt Speed Discontinuity

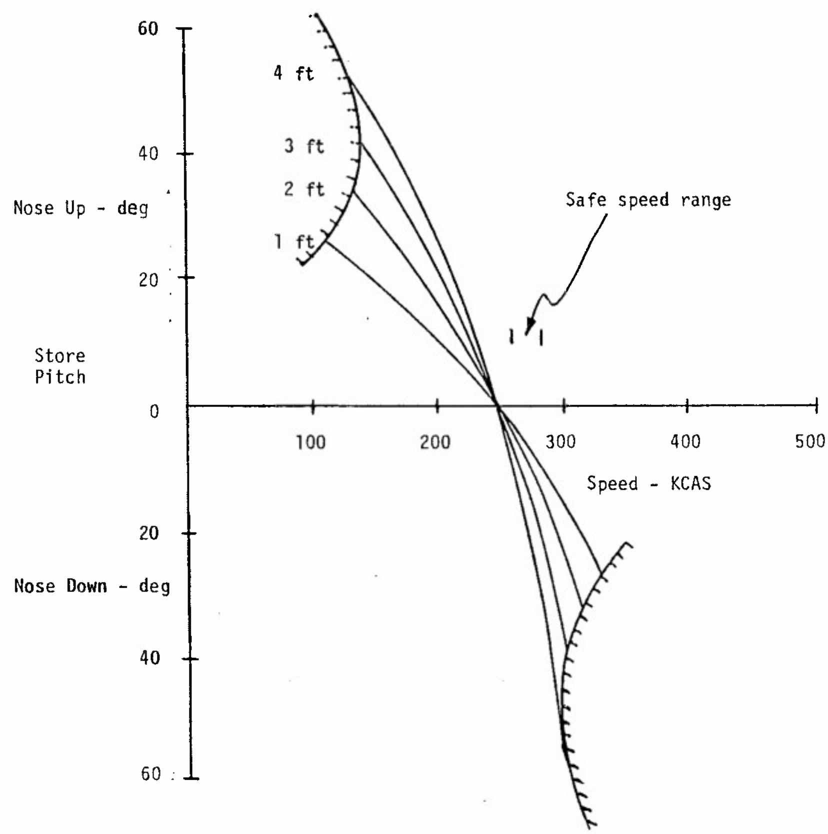


Figure 27 - Store Collision Boundary: Nose-Up and Nose-Down Pitching Motion

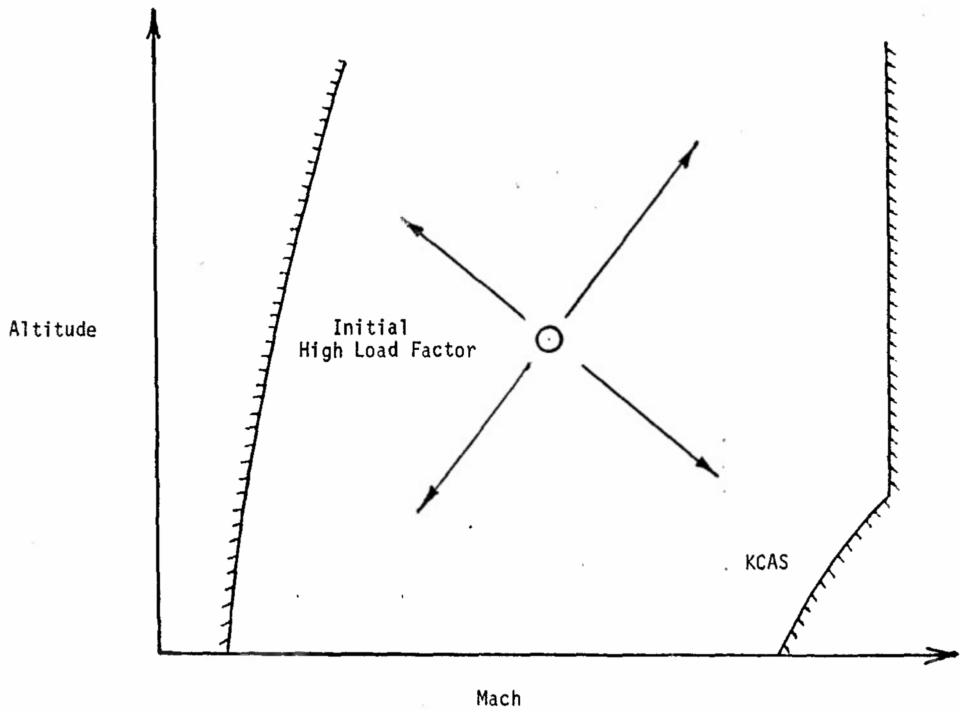


Figure 28 - Alternate Store Separation Test Approach

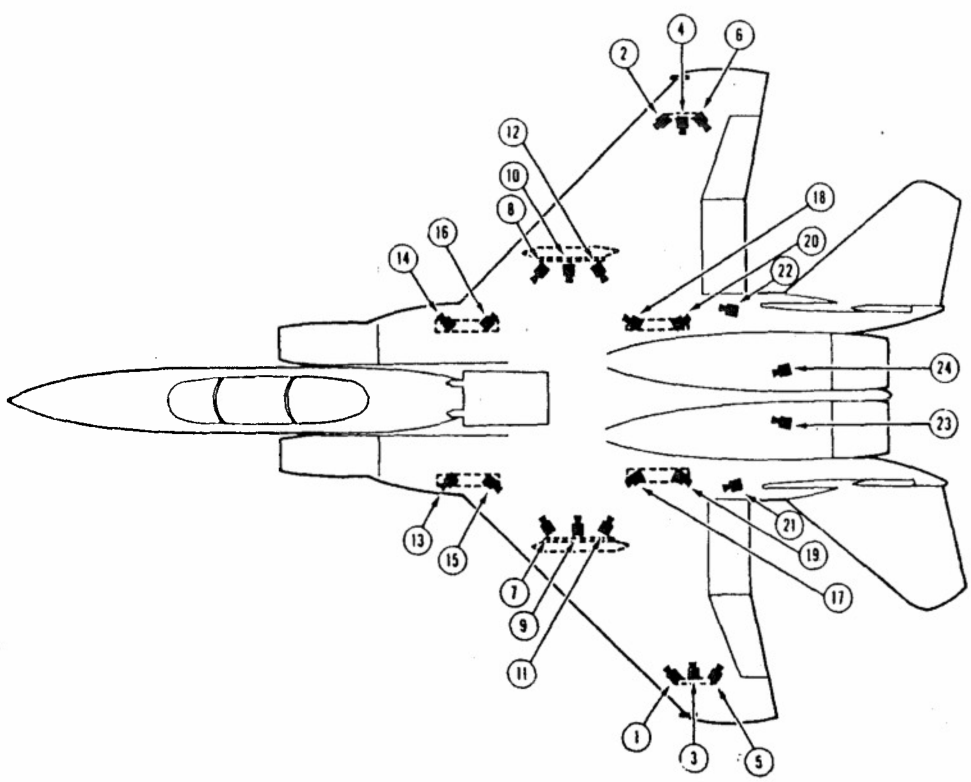


Figure 29 - Camera Locations Available on F-15 Aircraft

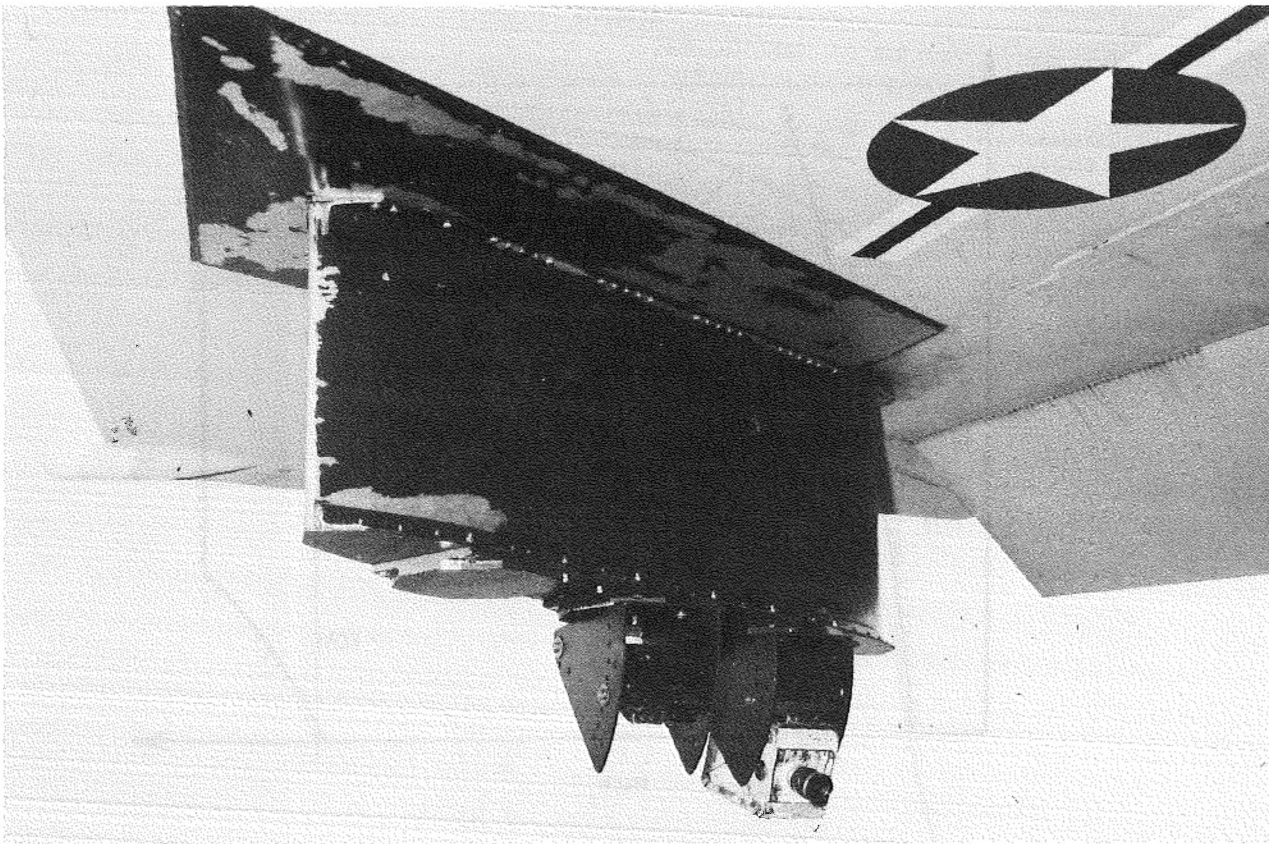


Figure 30 - F-15 Wing Pylon Mounted Camera Installation

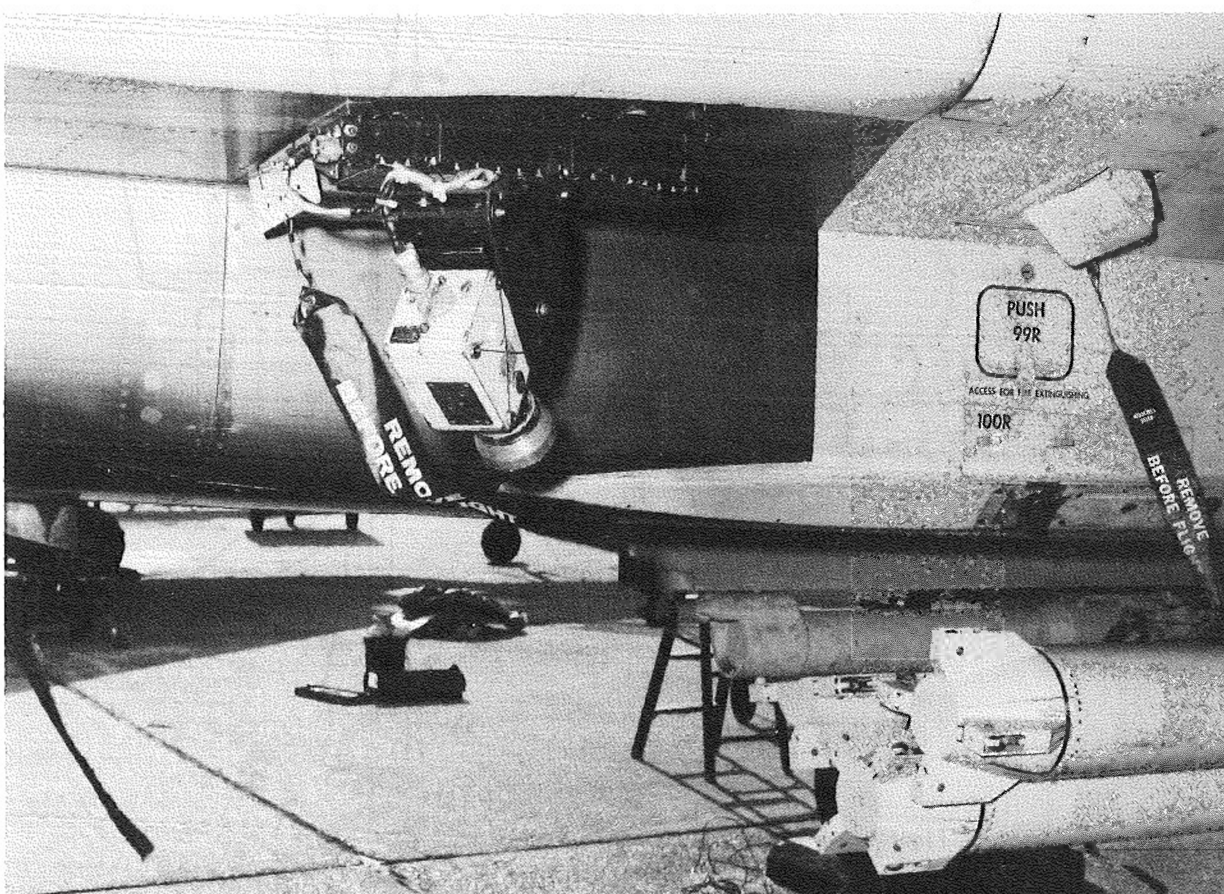


Figure 31 - F-15 Right Hand Rear Fuselage Mounted Camera Installation

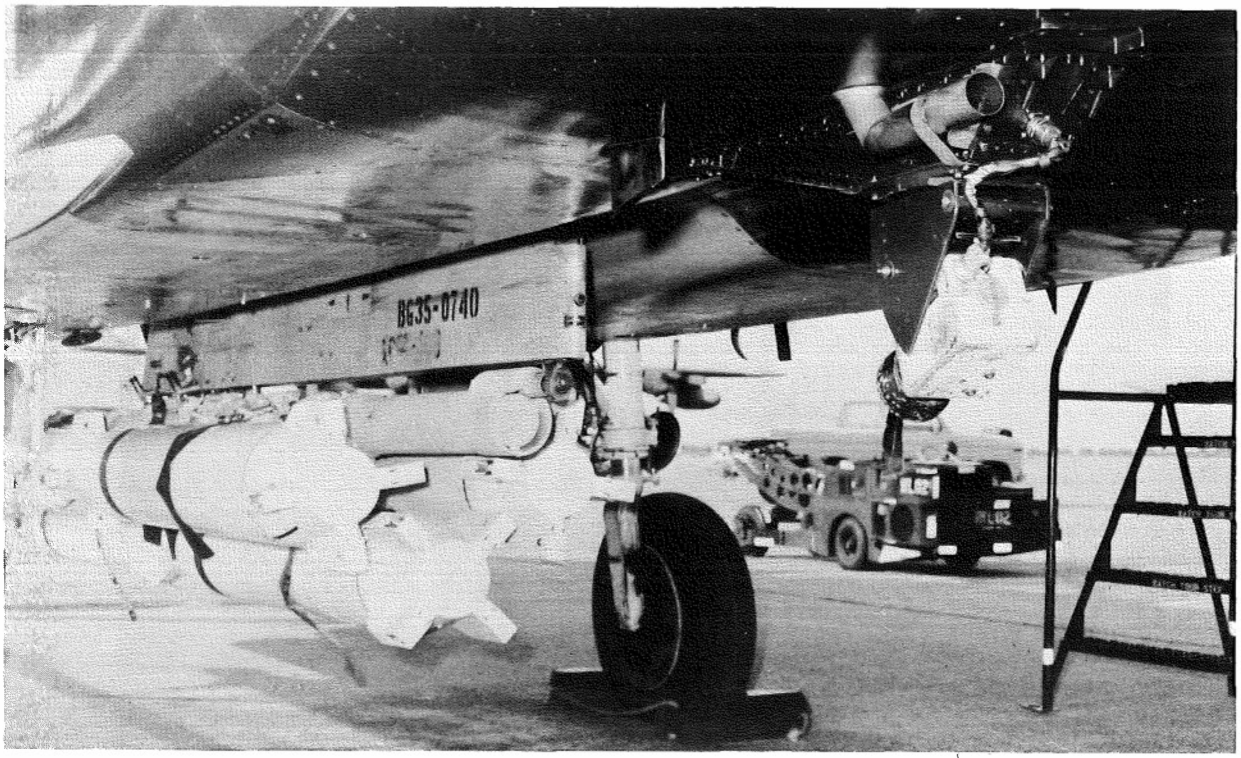


Figure 32 - F-15 Left Hand Rear Fuselage Mounted Camera Installation

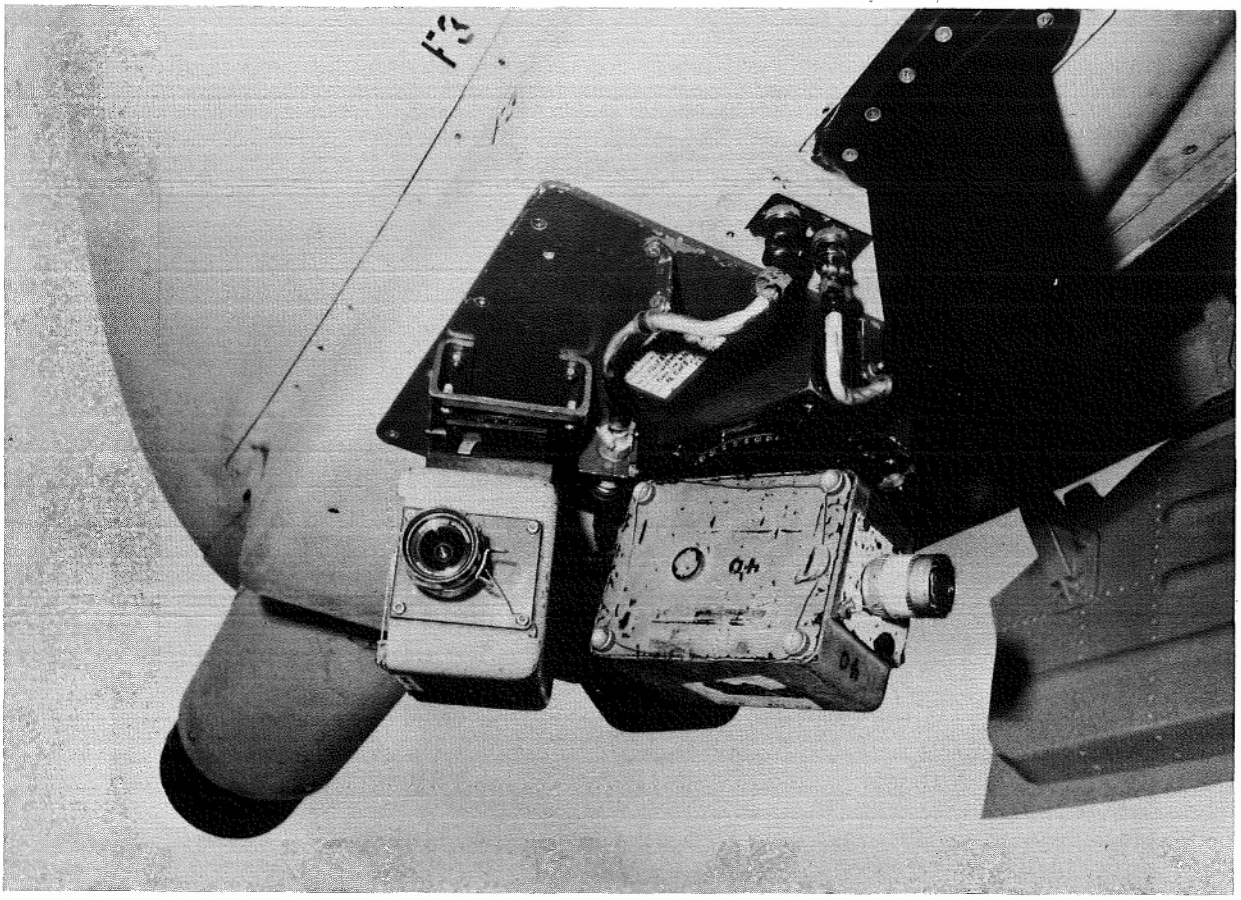


Figure 33 - A-10 Fuselage Mounted Double Camera Installation

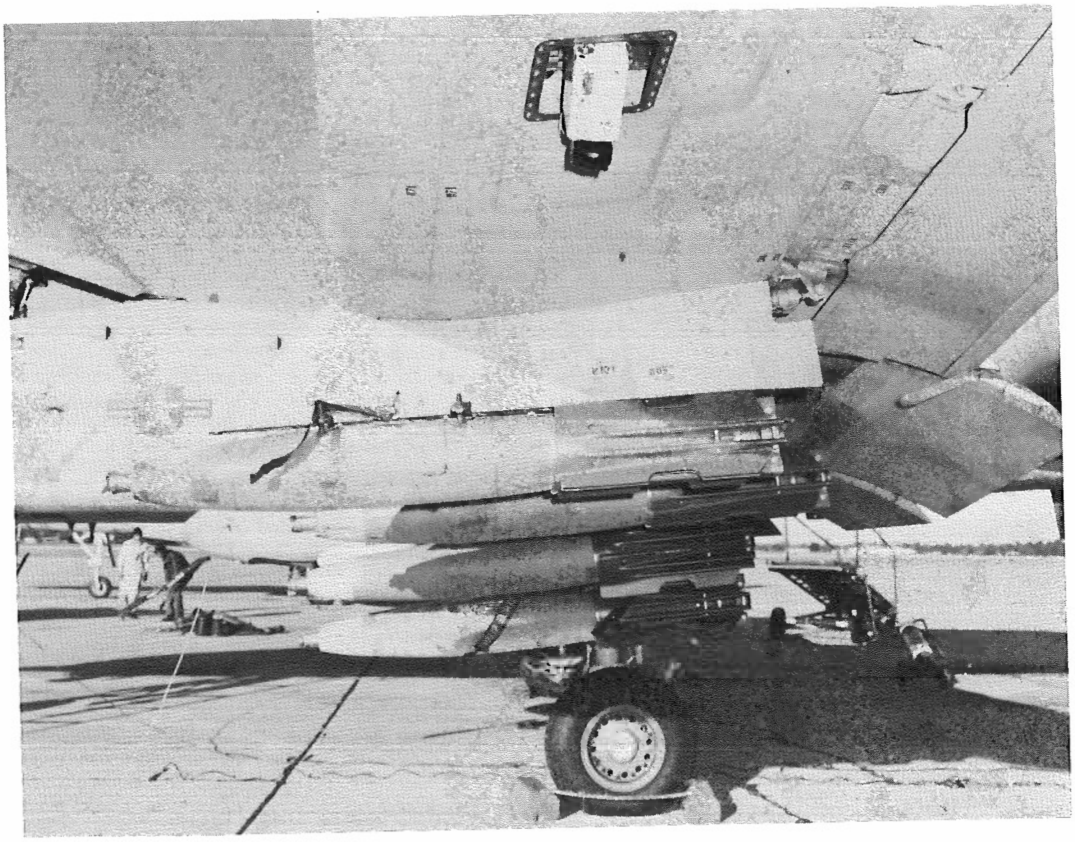


Figure 34 - A-10 Wing Mounted Camera Installation

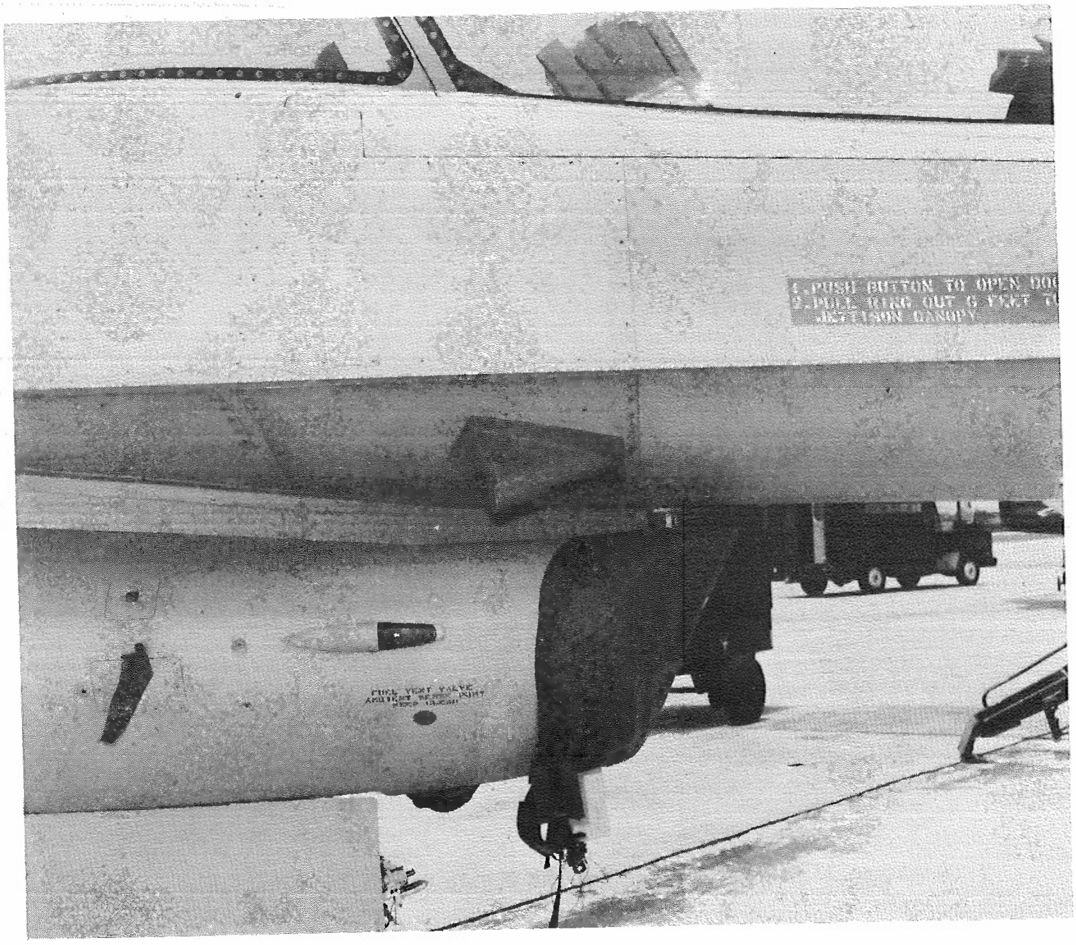


Figure 35 - F-16 Fuselage Mounted Camera Installation

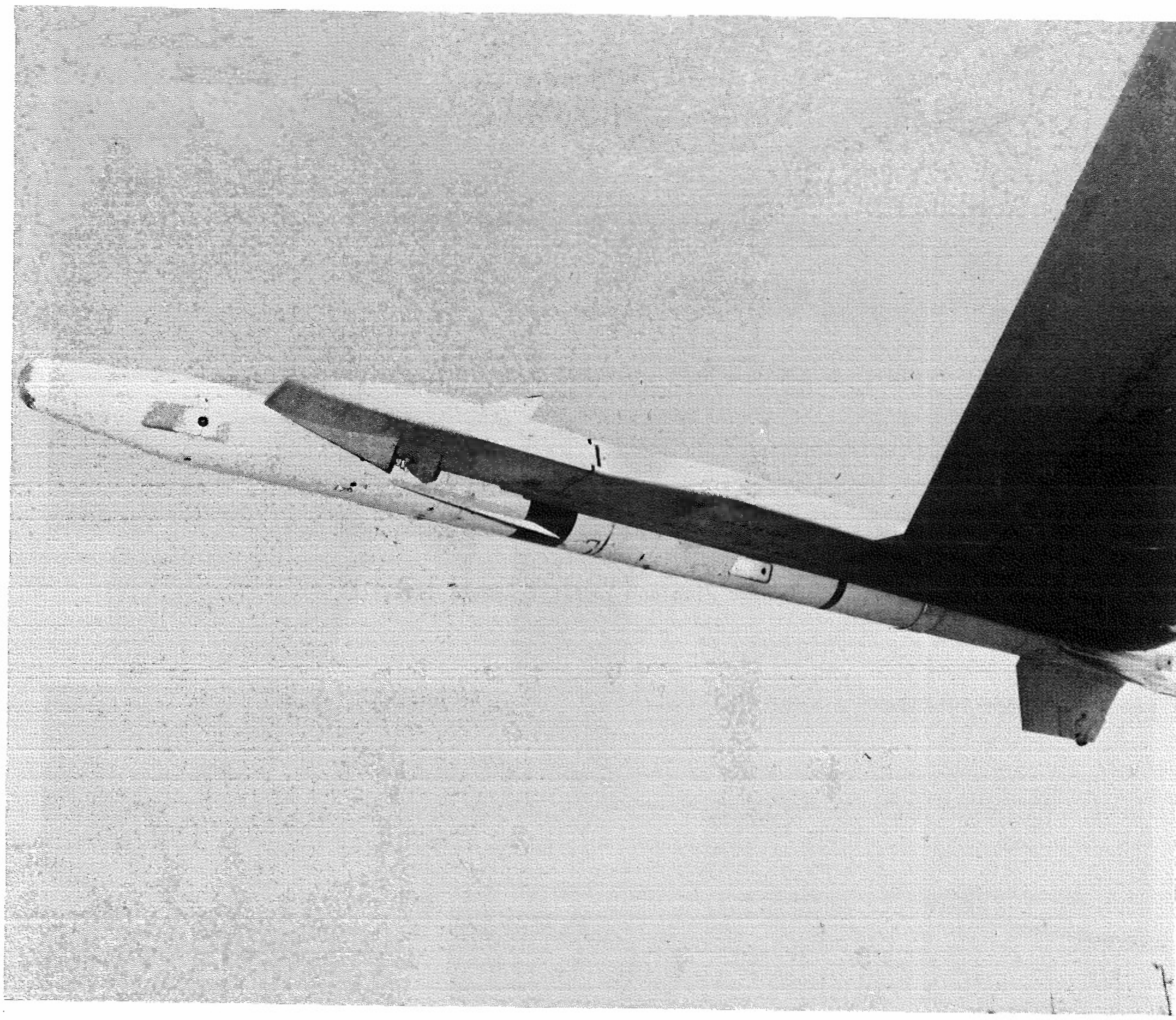


Figure 36 - F-16 Wing Tip Camera Installed in Dummy AIM-9

Figure 37 - A-7D Wing and Fuselage Camera Installations

Figure 38 - English Electric Valve Company CCD Camera

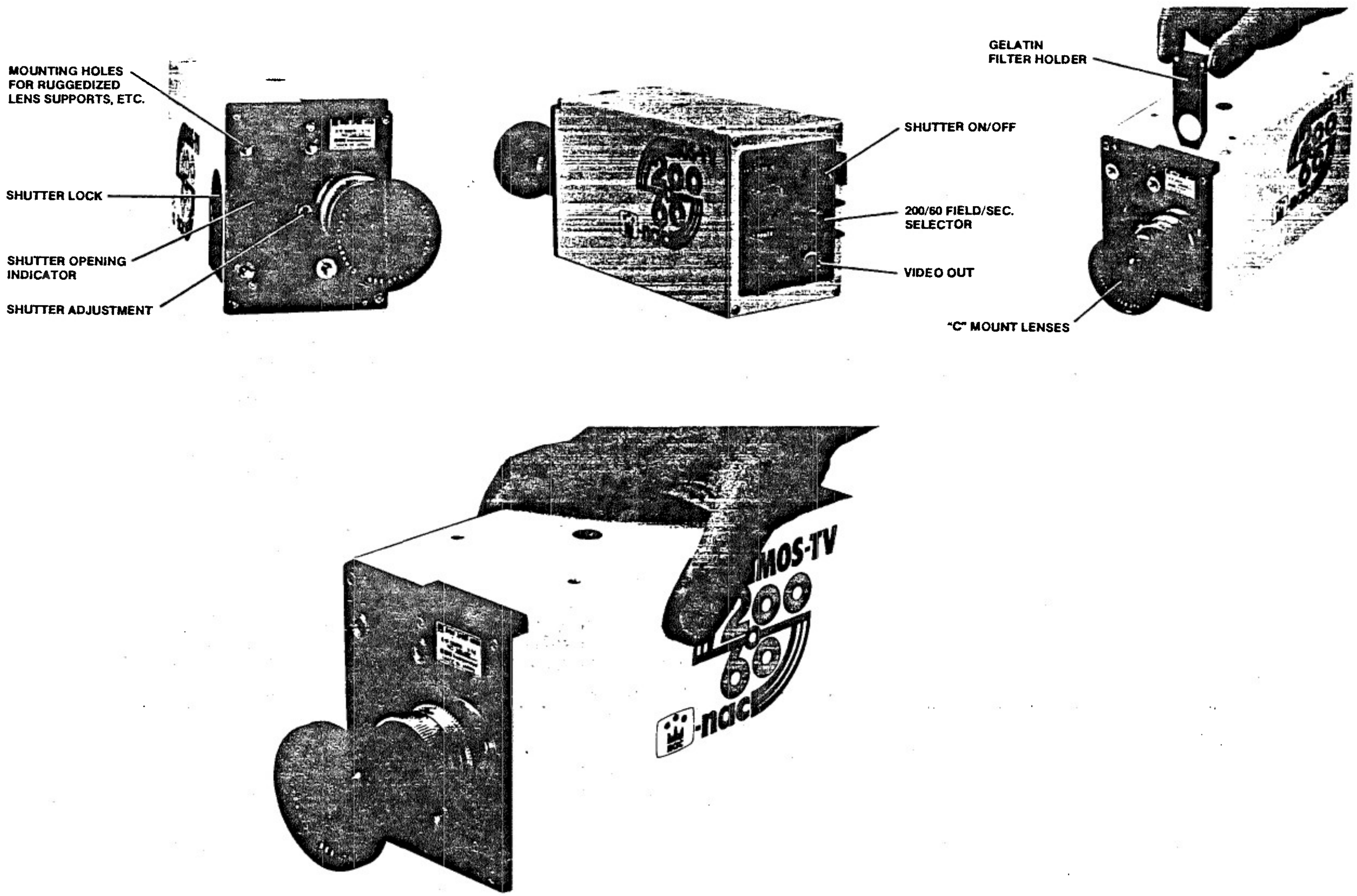


Figure 39 - Instrumentation Marketing Corporation CCD Camera

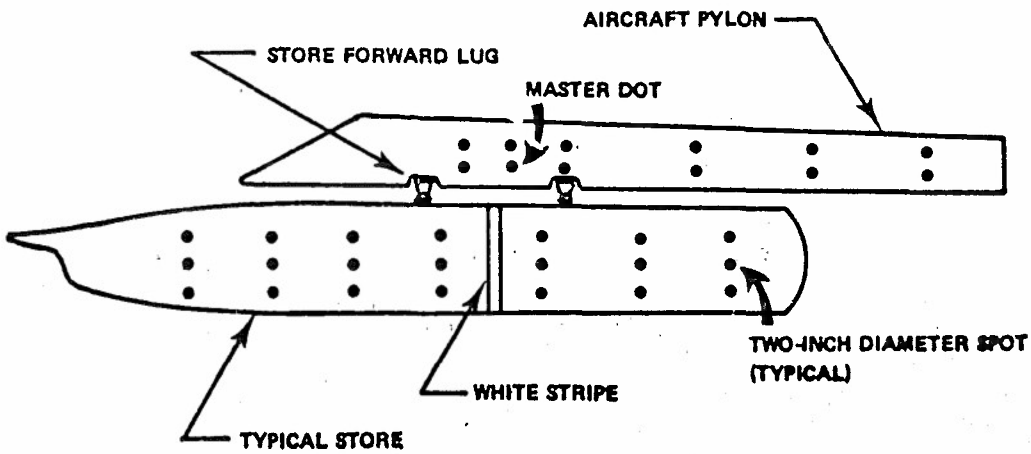


Figure 40 - Typical USAF Photogrammetry Store Paint Pattern

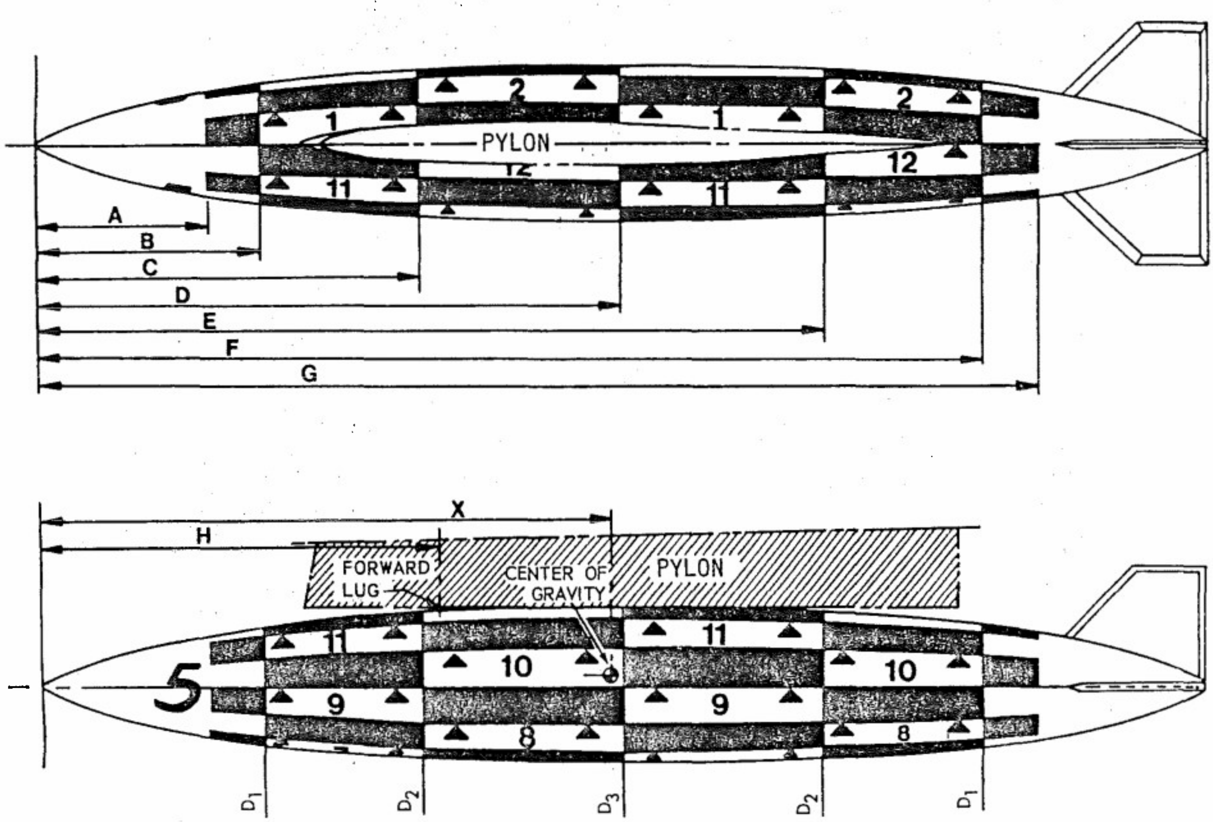


Figure 41 - Typical NLR Photogrammetry Store Paint Pattern

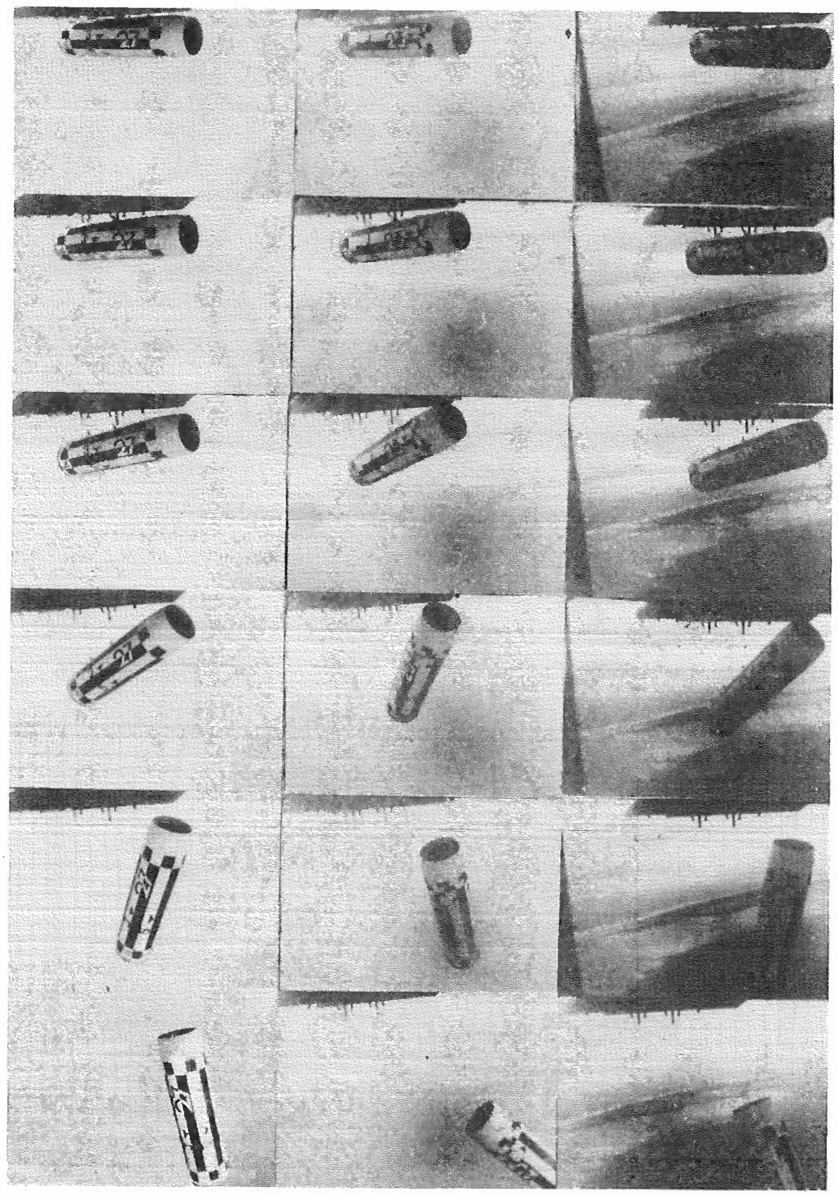


Figure 42 - Typical Film Strips Used by NLR for Data Reduction: Separation of LAU-3 Rocket Launchers from NF-5 with 25 Millisecond Release Interval Between Frames

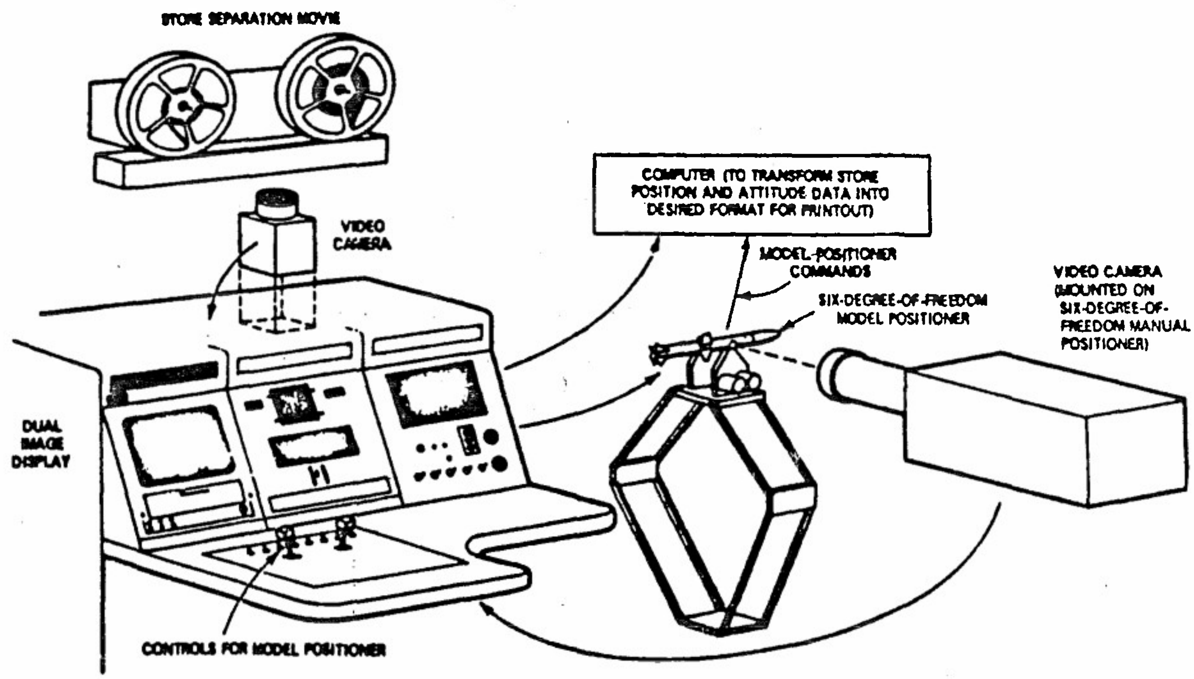


Figure 43 - PDAS Major Components

Mission No.	Test Date	Type of Store	Pylon No.	Station No.	Dive Angle	Normal Accel (g)	Airspeed (KCAS)	Altitude (ft/MSL)
207	9/16/76	CBU-58	9	T1	60	0.5	426	9500

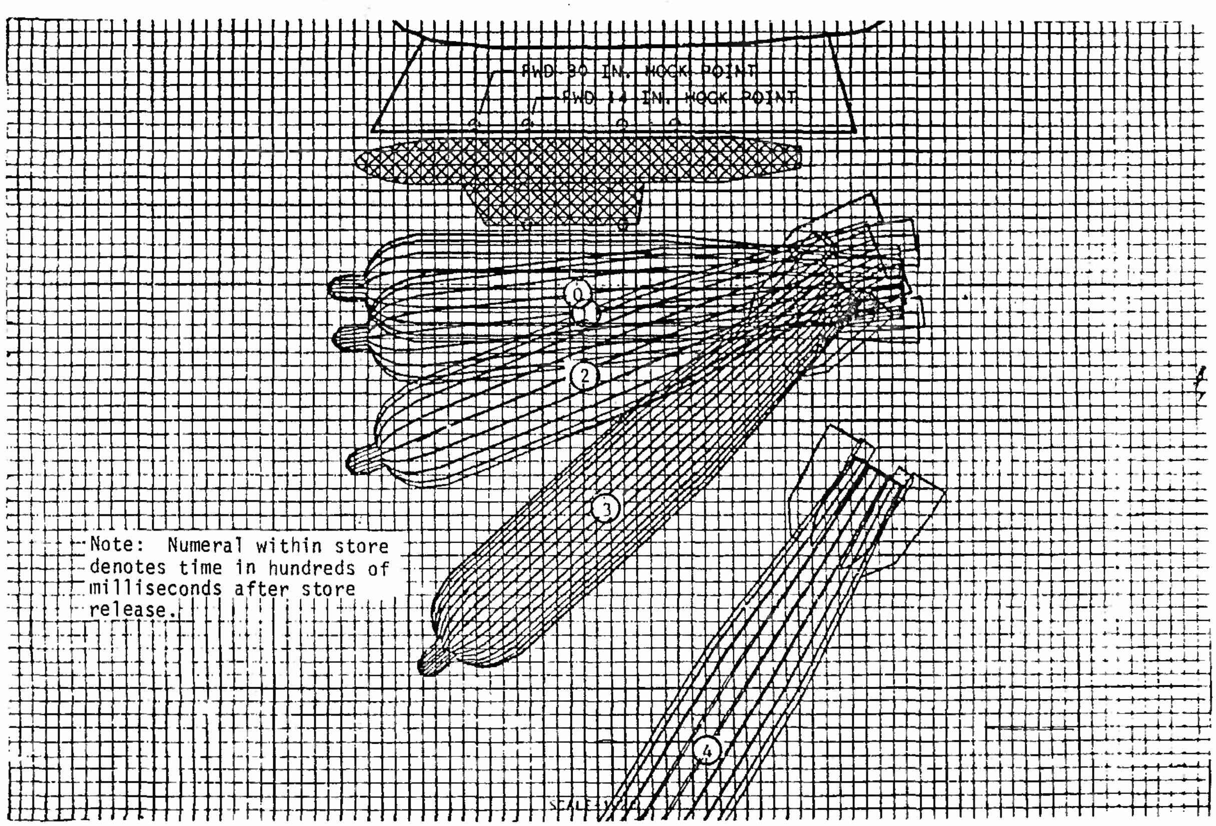


Figure 44 - Typical PDAS Graphical Data Presentation

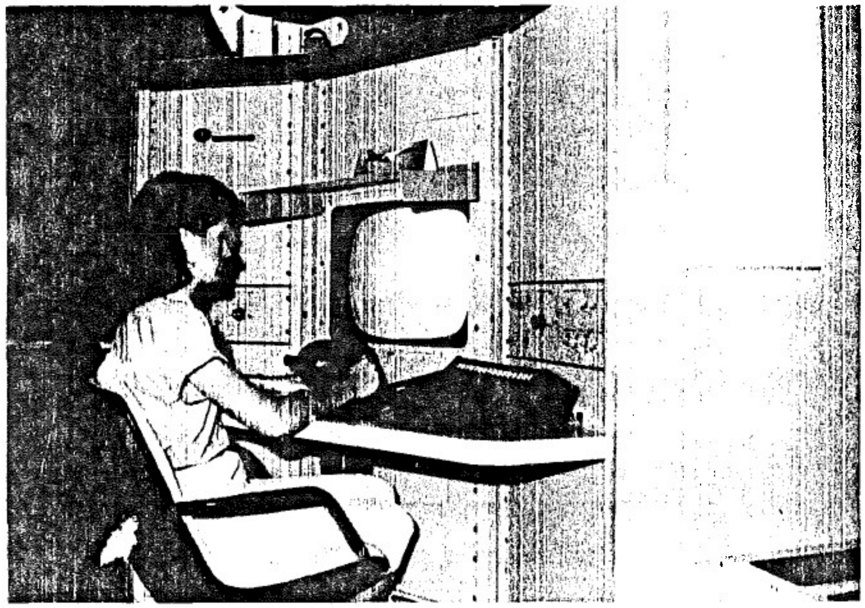


Figure 45 - GADS Operator Console

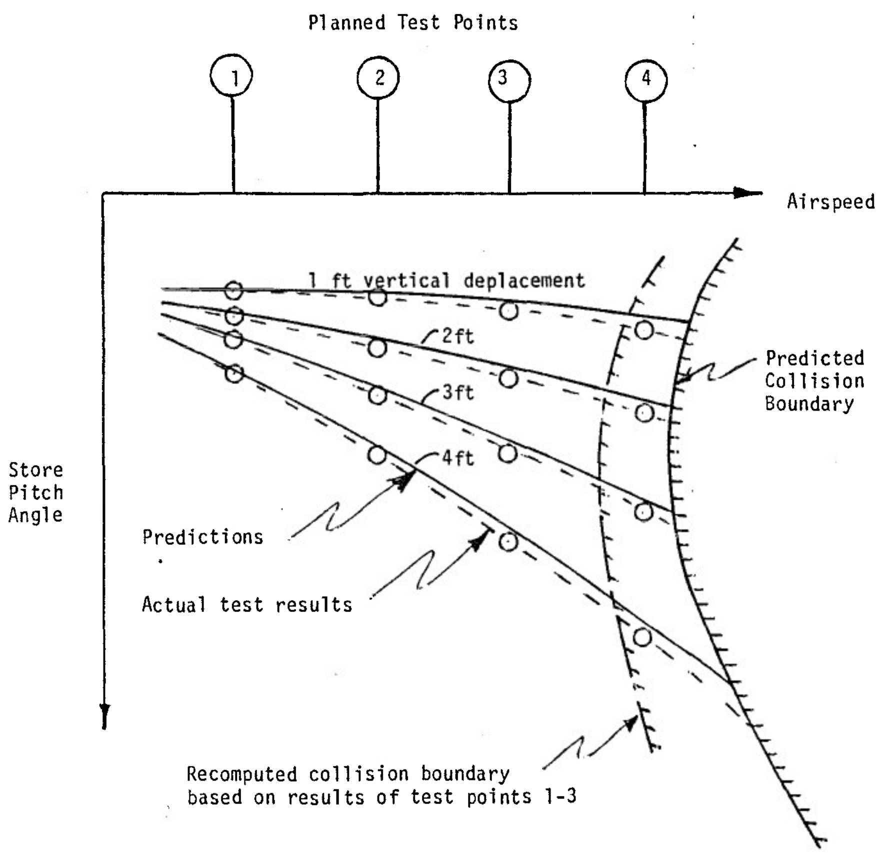


Figure 46 - Comparison of Actual Test Results with Predictions: Good Agreement

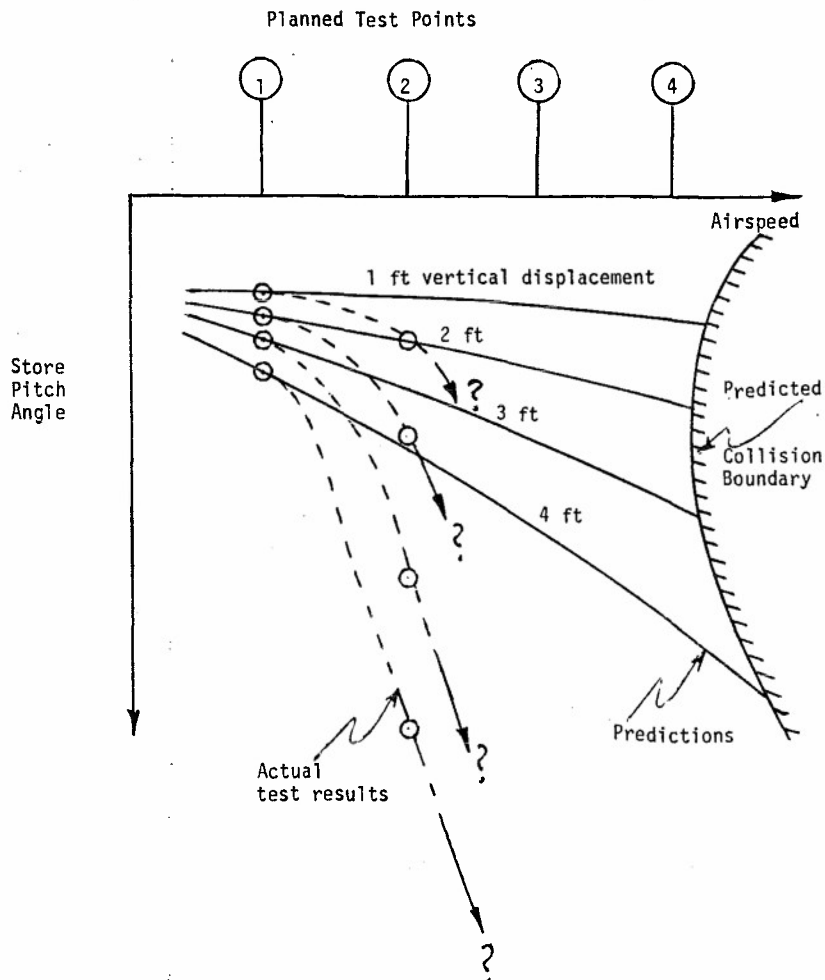


Figure 47 - Comparison of Actual Test Results with Predictions: Poor Agreement

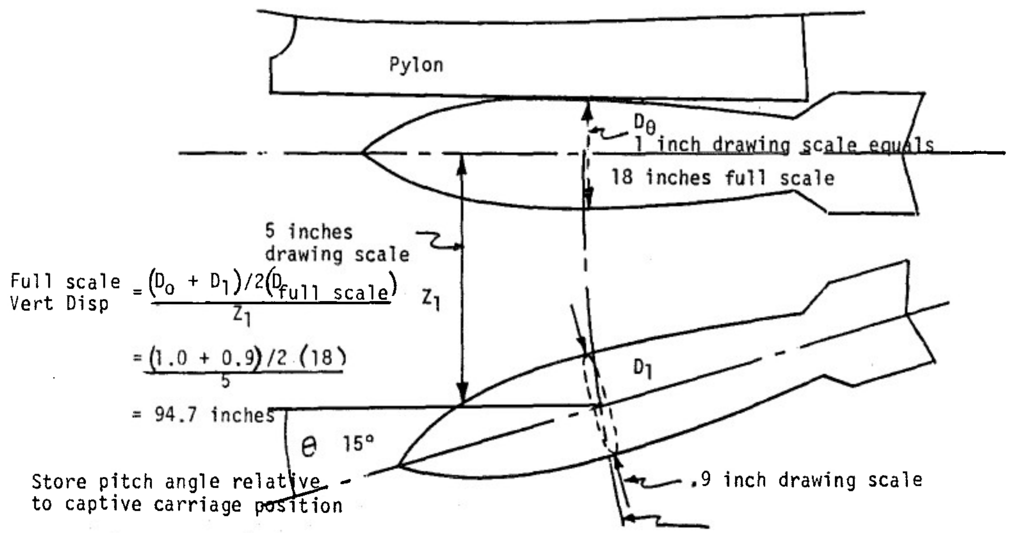
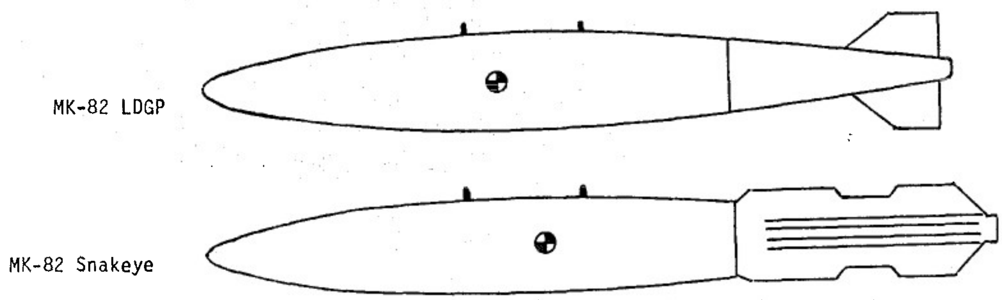


Figure 48 - Manual Scaling of Store Trajectory Data from Film



	Length	Diameter	Weight	Pitch Inertia	Center of Gravity
MK-82 LDGP	90.6 in.	10.8 in.	510 lbs.	37.5 slug-ft^2	6.6 in aft of fwd lug
MK-82 Snakeye	95.7 in.	10.8 in.	550 lbs	48.0 slug-ft^2	9.3 in aft of fwd lug

Figure 49 - Comparison of Geometric and Physical Characteristics of MK-82 LDGP and MK-82 Snakeye Bombs

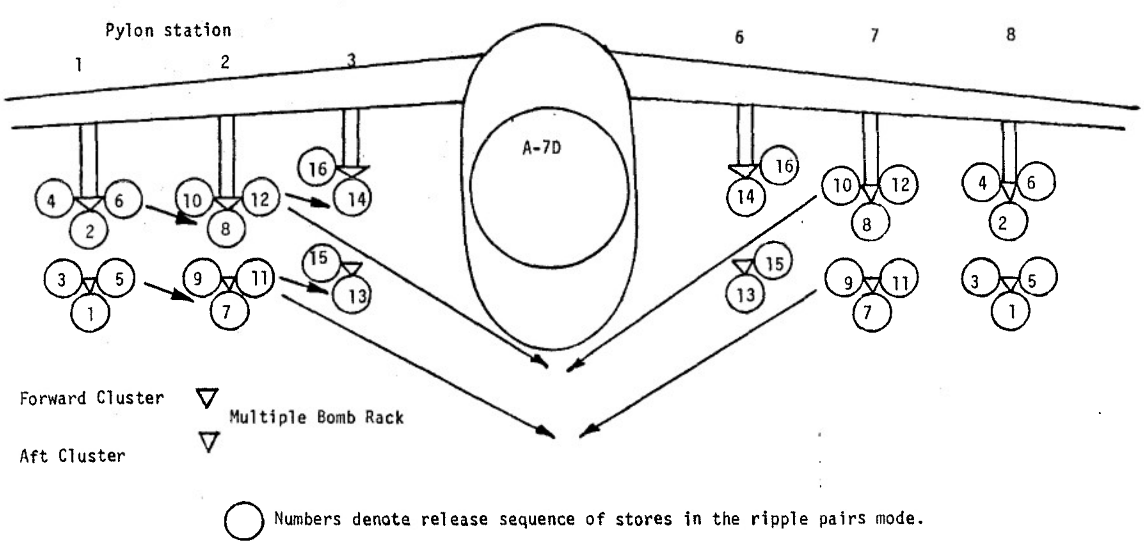


Figure 50 - Potential Stations for Store to Store Collisions in the Ripple Release Mode on an A-7

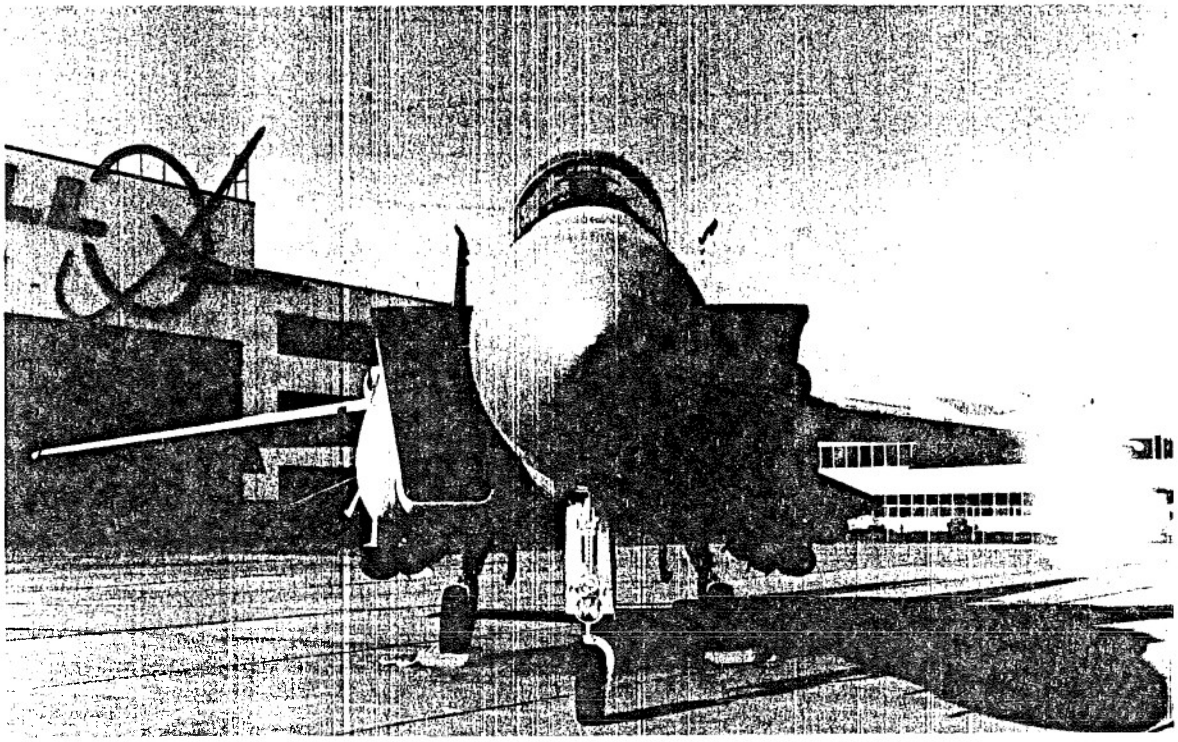


Figure 51 - F-15 with MK-82 Bombs Carried Tangentially

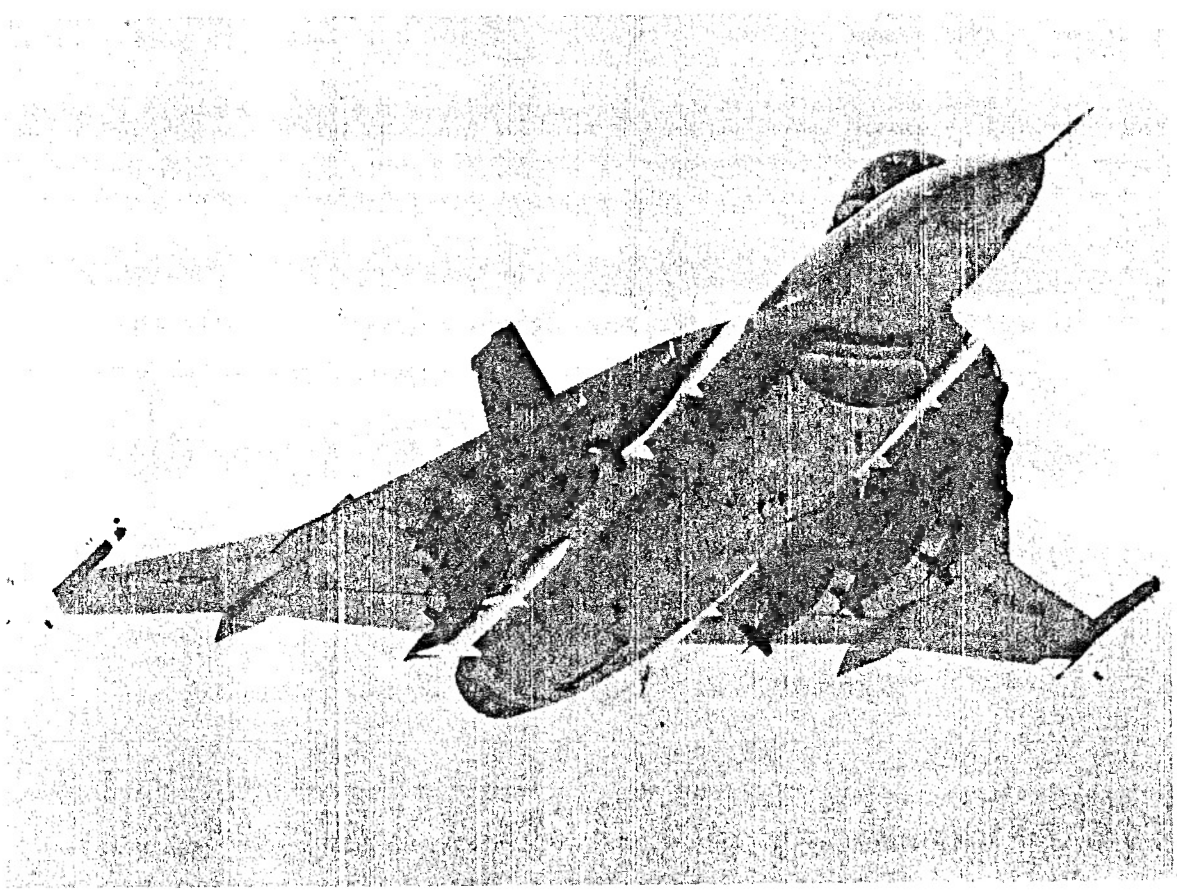


Figure 52 - F-16XL with MK-82 Bombs Carried Tangentially

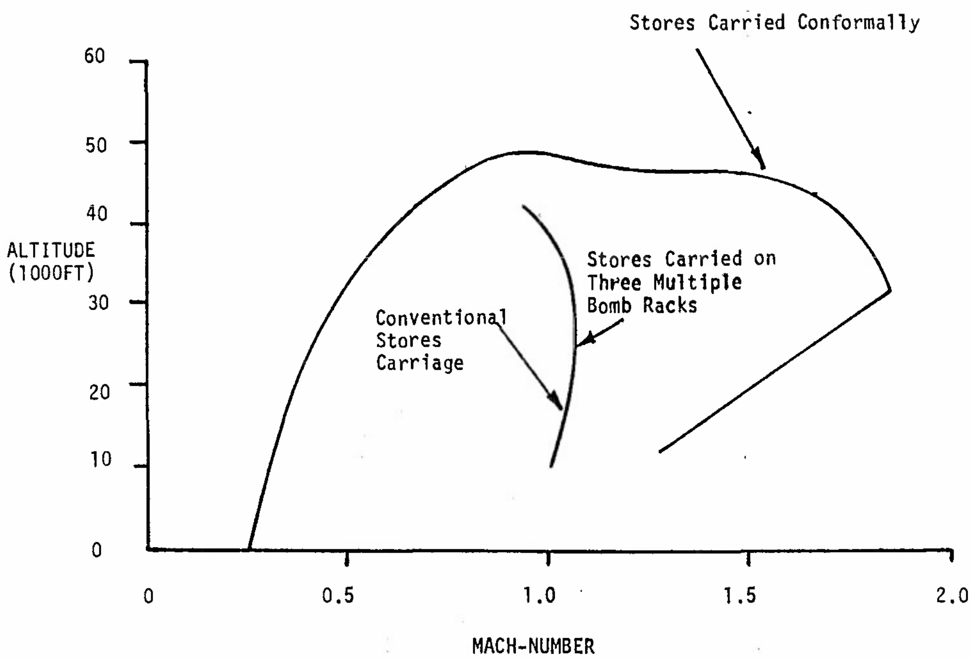


Figure 53 - F-4 Flight Envelope Extension with Twelve MK-82 Bombs Carried Conformally

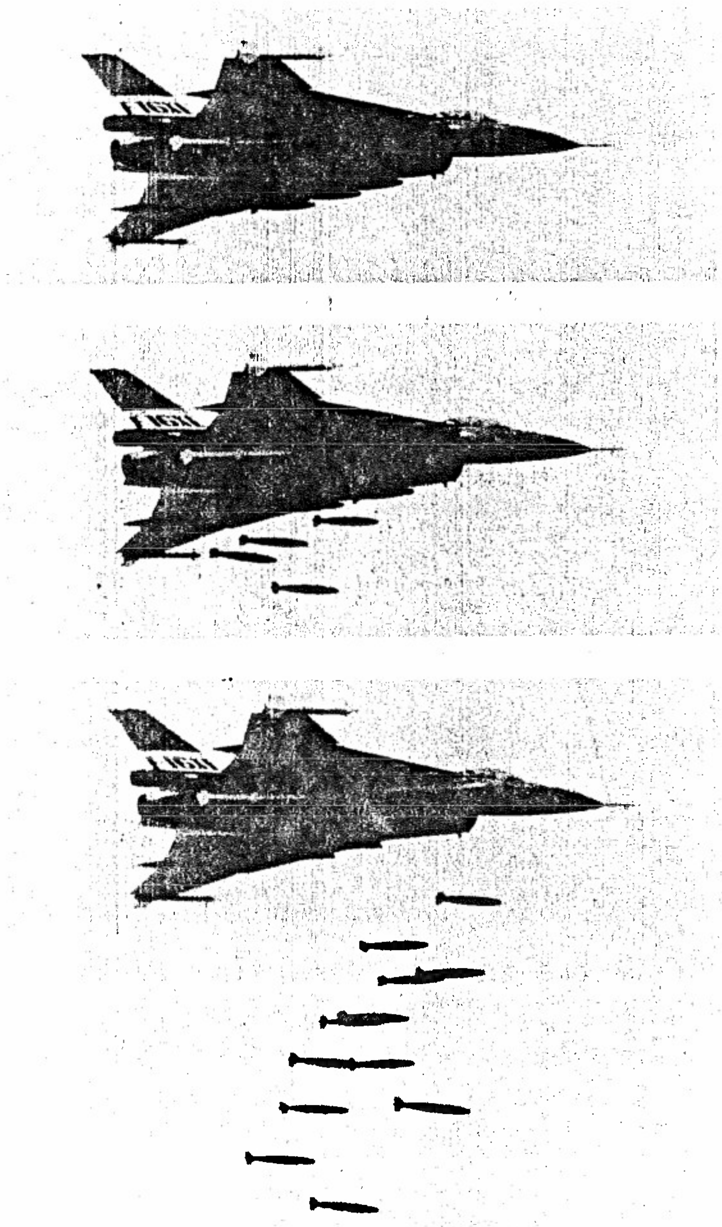


Figure 54 - MK-82 Bombs Separating from F-16XL at 550 Knots

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APPENDIX A

AERO MEMO 84-06

F-4/HARM MISSILE/LAU-118A LAUNCHER COMBINATION
JETTISON ANALYSIS

OFFICE FOR AIRCRAFT COMPATIBILITY
3246 TEST WING/TY

Eglin Air Force Base, FL 32542

APRIL 1984

NOTE: For the sake of brevity, only typical, representative, plots are included herein.

INTRODUCTION

TAC certification request 1982 formulized a request to certify the AGM-88/LAU-188A (HARM missile with launcher unit) for carriage and jettison on stations 1, 2, 8, and 9, of the F-4 aircraft. The desired carriage limits are a minimum of 550 KCAS/1.1 and the maximum limits the highest attainable limits for the missile/launcher combination. Maximum obtainable jettison limits were desired. Certification objectives established by DLCJ and DLCA were clarified with a desired limit of 650 KCAS/1.3 Mach.

The purpose of this memo is to predict the jettison characteristics of the HARM missile with its launcher and to recommend a flight test plan. This analysis considers only jettison of the HARM missile with its launcher and not the actual firing of the missile.

STORE CHARACTERISTICS

The AGM-130 missile is a High Speed Anti-Radiation Air-to-Ground Missile (HARM). The actual store considered in this analysis is the combined missile with its launcher (LAU-118A), with a combined weight of 879 lbs. Table 1 lists the mass and physical properties of the missile/launcher combination.

AERODYNAMIC DATA USED

Freestream and grid interference aerodynamic data for the missile/launcher combination were obtained in the four foot transonic (4T) wind tunnel at Arnold Engineering Development Center in a test in August of 1983. The captive trajectory test (TC746) is documented in Reference 1. Trajectory data were also collected using the Captive Trajectory Support System (CTS). The configurations tested are listed in Table 2. The drawings for the HARM missile/launcher combination model used in the wind tunnel test are in Figure 1. The missile/launcher combination simulated a wings fixed missile during release as a conservative approach. The missile in actual flight would have wings operating in trail to the local flow field.

The freestream aerodynamic data of the missile/launcher combination were compared to the freestream aerodynamic data of the HARM missile without the launcher. This was done to better understand the effects the launcher has on the missile.

The addition of the launcher to the HARM missile reduced the normal force and pitching moment of the missile. The pitching moment at = 0 degrees (Cm_0) for the missile alone is nearly zero. The addition of the launcher changed CM_0 of the missile to a negative value for all Mach numbers. The missile itself does not display much aerodynamic stability and the addition of the launcher unit does not change this fact. However, the misile itself is stable at large angles of attack; likewise, the missile/launcher combination is also stable at large angles of attack. Essentially, the stability of the missile/launcher combination is very similar to that of the HARM missile alone.

APPROACH

The trajectory simulation of this analysis used the DLCA six degree of freedom grid trajectory simulation computer program. The program uses freestream aerodynamic characteristics of the store, as well as the measured flow field (grid) interference coefficients induced by the parent aircraft to predict the separation trajectory. In Appendix A, thee is a representative control card string and input list to initiate the simulation program.

The trajectory is then represented using a graphics computer program which produces three orthogonal sets of pictures of the store separating from the aircraft. This is a useful tool in helping to determine collision boundaries and separation characteristics of the store. All separations are illustrate as right wing releases even though some of the configurations tested are on left wing of the wind tunnel model. These left wing releases were mirror imaged onto the right wing only for illustrating the separation of the store from the F-4 aircraft.

As a first step to verify grid data used in the simulation, the grid simulation trajectories were compared to representative full CTS trajectori acquired on line during the wind tunnel test. These is done to verify the aerodynamic data and ascertain that the program has been properly initiali Using the trajectory program, a sensitivity analysis was completed to understand configuration effects, Mach number effects, altitude/dynamic pressure effects, angle of attack effects, damping derivative effects and varying mass properties effects.

The configurations tested in the wind tunnel and simulated in the prog are representative of the configurations requested by the TAC certificatio recommendation. All the configurations were simulated at an altitude of feet with a load factor of 1.0g in level flight. The calibrated airspeed knots/Mach number ranged from 350/1.75 to 860/1.3. In the subsonic regime angle of attacks ranged from zero to four degrees in increments of two degr and in the supersonic regime, the angles of attack were zero and two degree.

All the configurations tested simulated a MAU-12 cartridge/orifice settings of two 863 cartridges with orifice settings of .156 (fwd)/blank (aft). This type of cartridge/orifice combination provides a total ejector force of 3250 lbs and creates a positive (nose up) ejector moment of 562.25 ft-lbs.

As in the wind tunnel tests, the store was modeled as a fixed wing store during its release. This approach ensures uniformity for comparisons of the simulations with the CTS data.

Of the six configurations tested, four of them had CTS (trajectory) data in order that comparisons could be done with the simulation program to verfy the program ability to predict trajectories accurately. Figures 2 through 7 show representative plots of the grid simulation trajectories versus CTS trajectories for two of the tested configurations. Figures 2, 3, and 4 demonstrate the grid simulations program predicted pitch and yaw quite well, for configuration 101. In figures 5, 6, and 7 the program predictions are very accurate for this configuration - configuration 104.

Although only two configurations are presented here, the other two configurations displayed similar results. This proves that "limited grid" can be used to predict store trajectories as well as "full grid" or CTS. Once the store angle of attack exceedes 26 degrees, the accuracy of the simulation decreases rapidly and, therefore, is not dependable beyond this point.

SIMULATION RESULTS

The three view illustrations of four representative configurations are included in figures 8a through 11b for selected jettision conditions. In all cases, the store pitches down even though the applied ejector force causes a positive (nose up) ejector moment and the store rolls inboard and yaws outboard. This downward pitch of the store is a desirable trait for safe separation of a store from an aircraft.

a) Configuration Effects

Figures 12a through 13c demonstrate the effects different configurations will have on the store's trajectory. In all cases configurations 102 and 104 show a larger downward pitch than in configurations 101 and 106. The difference in pitch between configurations 102 and 104 and configurations 101 and 106 can be up to 15 degrees at a point four to five feet below the aircraft. Once again, Configuration 104 displays larger outboard yaw of all four configurations. Configuration 102 did not display any real pattern. This difference in yaw in Configuration 104 from all the others can be up to 15 degrees at a point four to five feet below the aircraft. The difference in configurations do have a very significant effect on the store trajectory. In terms of pitch and yaw rates, the worst configuration would be Configuration 104. From a physical standpoint, Configuration 106 can be considered a worst case. The store in this case is released from the inboard station and is required to clear a larger area than in Configuration 104.

b) Mach Number Effects

Figures 14a through 15d show Mach effects for four configurations at two different angles of attack. The calibrated airspeed in knots (KCAS) was held constant at 600 KCAS for each Mach number and angle of attack.

In pitch, Mach number has some effect. Between M = .95 and M = 1.3 maximum difference in pitch is about seven degrees, five feet below the aircraft and 12 degrees, eight feet below the aircraft. But most of the configurations display small differences in pitch. In general, as Mach number increases, the tendency is for downward pitch to remain the same or decrease.

Mach number has a different effect on yaw. Between M = .95 and M = 1.3 the maximum difference in yaw is about 20 degrees, five feet below the aircraft and 30 degrees, nine feet below the aircraft. In almost all cases, as the Mach number increases outboard yaw increases.

Pitch rates and yaw rates were investigated to determine the effects Mach number may have on these rates. The Mach number had little effect on the pitch rate, although the yaw rates in the supersonic regime were significantly different from the yaw rates in the subsonic regime.

c) Altitude/Dynamic Pressure Effects

Figures 16a through 18d demonstrate the effects altitude/dynamic pressure has on the store's trajectory for all the configurations and selected aircraft angles of attach. The altitude/dynamic pressure does have some effect on the store's trajectory, although it's only slight. The tendency is for the store's downward pitch and outboard yaw to decrease with increasing altitude.

d) Angle of Attack Effects

Figures 19a through 21d illustrate the effects on pitch and yaw of the store as the aircraft angle of attack is varied. both pitch and yaw are affected. At M = .95 between AOA = 0 and AOA = four degrees, pitch differs by about eight degrees and yaw differs by about 12 degrees, five feet below the aircraft. At M = 1.1 and M = 1.3, between AOA = 0 and AOA = two degrees, pitch differs by about six degrees while yaw differs by about five degrees, five feet below the aircraft. In general, as the aircraft angle of attack increases, downward pitch decreases and outboard yaw increases.

e) Damping Derivative Effects

The values used for the damping derivatives where those estimated values for the HARM missile without its launcher. These values came from reference 2. To account for the launcher and the approximated values obtained, Cnr and Cmq were varied to determine possible effects these damping derivatives may have on the store's trajectory. Figures 22a through 24c show that changes in the damping derivatives have little effect on the store's trajectory.

f) Varying Mass Properties Effects

The Center of Gravity (CG) of the store was varied to determine the effects on the store's trajectories. The minimum CG limit used was 6.9 feet from the nose of the missile. The maximum CG limit used was 7.9 feet from the nose of the missile. Figures 25a through 27d show the CG effects for aircraft angle of attack of zero degrees.

The variation of the store CG has a significant effect in pitch and yaw. Between CG = 6.9 feet and CG = 7.9 feet, the maximum difference in downward pitch is 13 degrees, five feet below the aircraft and 23 degrees, nine feet below the aircraft. Within the specified limits, outboard yaw differs by a maximum of seven degrees, five feet below the aircraft and 20 degrees, nine feet below the aircraft. In general, as the store CG position moves aft, downward pitch and outboard yaw increase.

FLIGHT TEST RECOMMENDATION

In the subsonic regime, the trajectory simulations of all four configurations looked at displayed smooth characteristics of the store. The downward pitch is not excessive and there is little or no yaw of the store after release. This is not the case in the supersonic regime. At 625 KCAS/1.1 and 735 KCAS/1.3, nose downward pitch and outboard yaw trends are considerably more rapid than in the subsonic regime.

Another item to consider is the acquisition of the required flight test assets. These assets are very expensive and difficult to obtain. Therefore, it would be desirable to keep flight test costs to a minimum.

Also, recent flight test films were reviewed of a similar missile to the HARM and the AGM-45 missile. The AGM-45 missile displayed a very smooth and excellent release up to 550 KCAS/.95 from the F-4 inboard station. Although this missile did not have the launcher released with it, it's expected that a comparison can be made between the HARM missile and the AGM-45 missile. The AGM-45 missile is a lighter weight vehicle release without vertical ejection.

In view of this information, it is desired not to flight test at 550 KCAS/.95. But this is not the case in the supersonic regime. For safety considerations and, also, because it's general philosophy that supersonic jettison of a store be demonstrated, flight testing will be required in the supersonic regime.

Two flight tests will be required. The first test should be at 600 KCAS/1.1 with the HARM missile/launcher combination being jettisoned from the inboard station number 2. The second test should be at 650 KCAS/1.3 with the HARM missile/launcher combination being jettisoned from the inboard station number 2. This second flight test should be done after films from the first flight test have been reviewed. All releases should be at 1.0g loading and in level flight. Figure 28 illustrates the configurations and flight profiles for these flight tests. GADS data are requested for all the missions.

SUMMARY

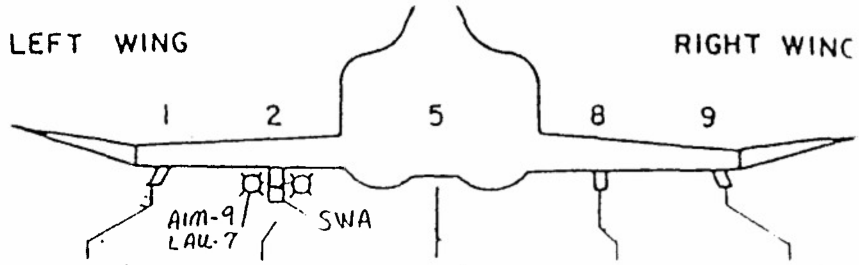
Based on the trajectory simulations, it's expected the HARM missile/launcher combination can be jettisoned safely from an F-4 aircraft. The initial tendencies are to pitch down and yaw outboard. Upon successful completion of proposed flight tests, the HARM missile/launcher can be cleared on the F-4 aircraft to possible limits of 650 KCAS/1.3 at 1.0g loading for jettison in the requested configurations.

Table 1

HARM AGM-88 with LAU 118/A Mass and Physical Properties

Store Weight (lbs)	879.0
Diameter (ft)	0.833
Reference Area (ft^2)	0.545
Length (ft)	13.667
Fwd lug location Aft of the nose (ft)	7.150
Center of Gravity Location Aft of fwd lug (in)	2.925
Rolling Moment of Inertia Ixx (slug-ft^2)	7.2
Pitching Moment of Inertia Iyy (slug-ft^2)	345.00
Yawing Moment of Inertia Izz (slug-ft^2)	340.00
Cross Product of Inertia Ixz (slug-ft^2)	3.42
* Roll Damping Derivative CLP (1/radian)	-100.00
* Pitch Damping Derivative CMQ (1/radian)	-1000.00
* Yaw Damping Derivative CNR (1/radian)	-1000.00

* NOTE: Damping Derivatives are for the HARM missile without its launcher.



CONFIG	OUTB'D	INB'D	CNTRLINE	INB'D	OUTB'D
101	370 GAL TANK	AGM-88/ LAU-118/A	MK-20	GPU-5A	EMPTY
102	↓	EMPTY	↓	↓	AGM-88/ LAU-118/A
103	EMPTY	CBU-58/B	600 GAL TANK	AGM-65 LAU-88	↓
104	AGM-88/ LAU-118/A	↓	↓	↓	EMPTY
105	↓	AGM-88/ LAU-118/A	MK-20	EMPTY	370 GAL TANK
106	EMPTY	↓	↓	AGM-88/ LAU-118/A	↓

DENOTES METRIC STORE

DENOTES DUMMY STORE

DENOTES TER

CLEAN DENOTES PYLON REMOVED

EMPTY DENOTES NO STORE ON PYLON

DENOTES MER

Table 2
Wind Tunnel Test Configurations

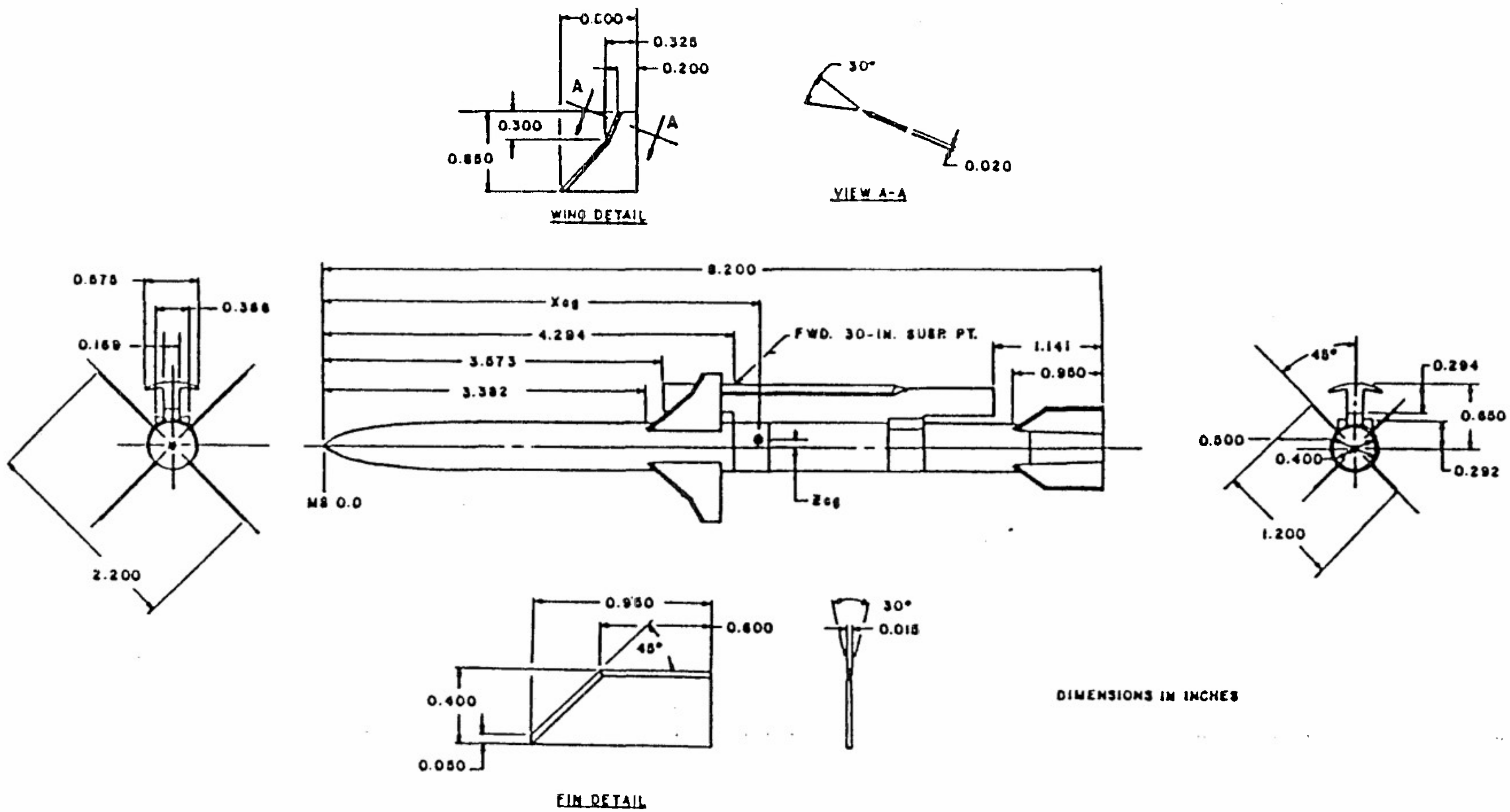


Figure 1
.05 Scale Model of AGM-88/LAU-118/A

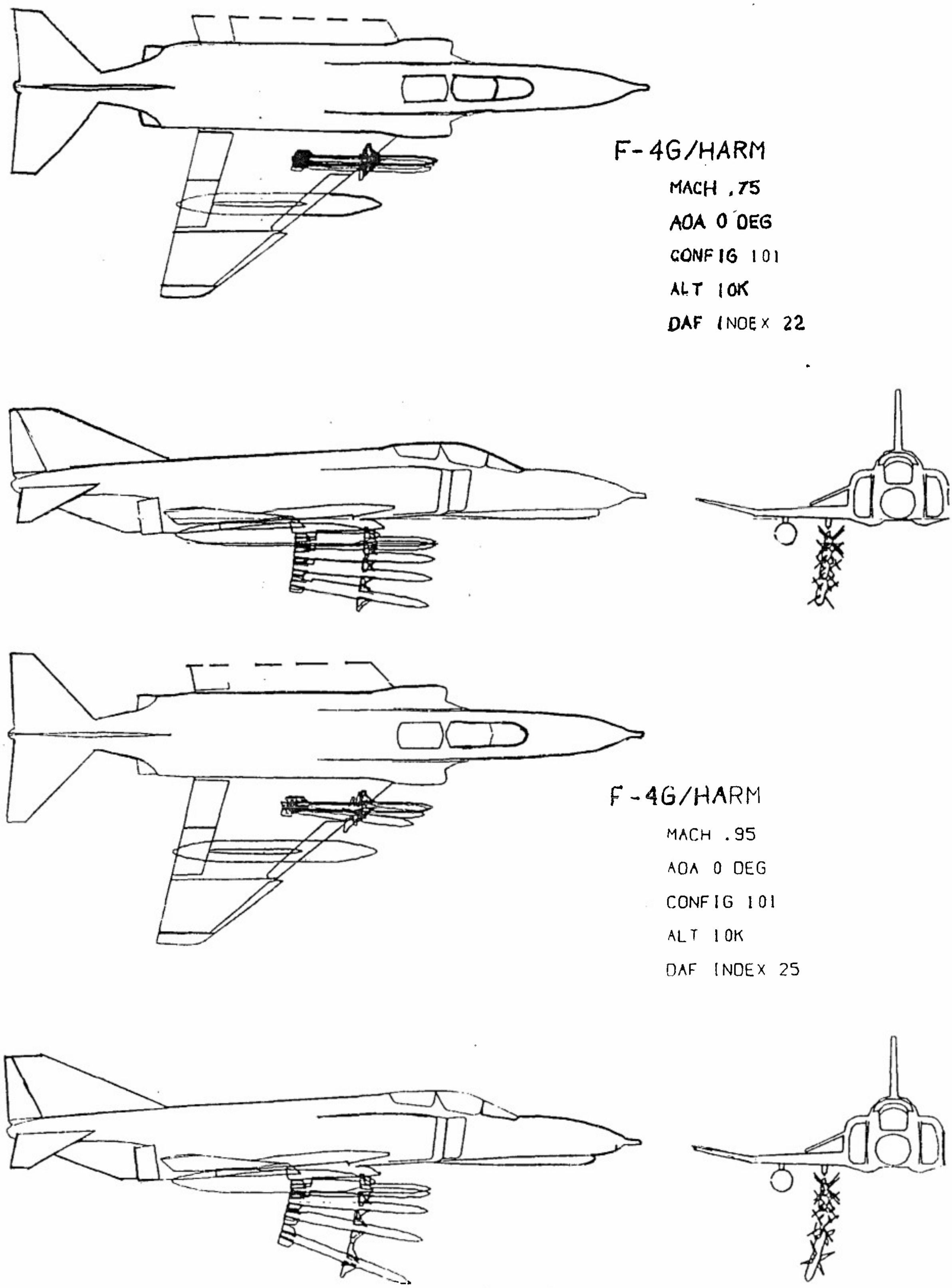


Figure 8a- Trajectory Simulations
(Config 101)

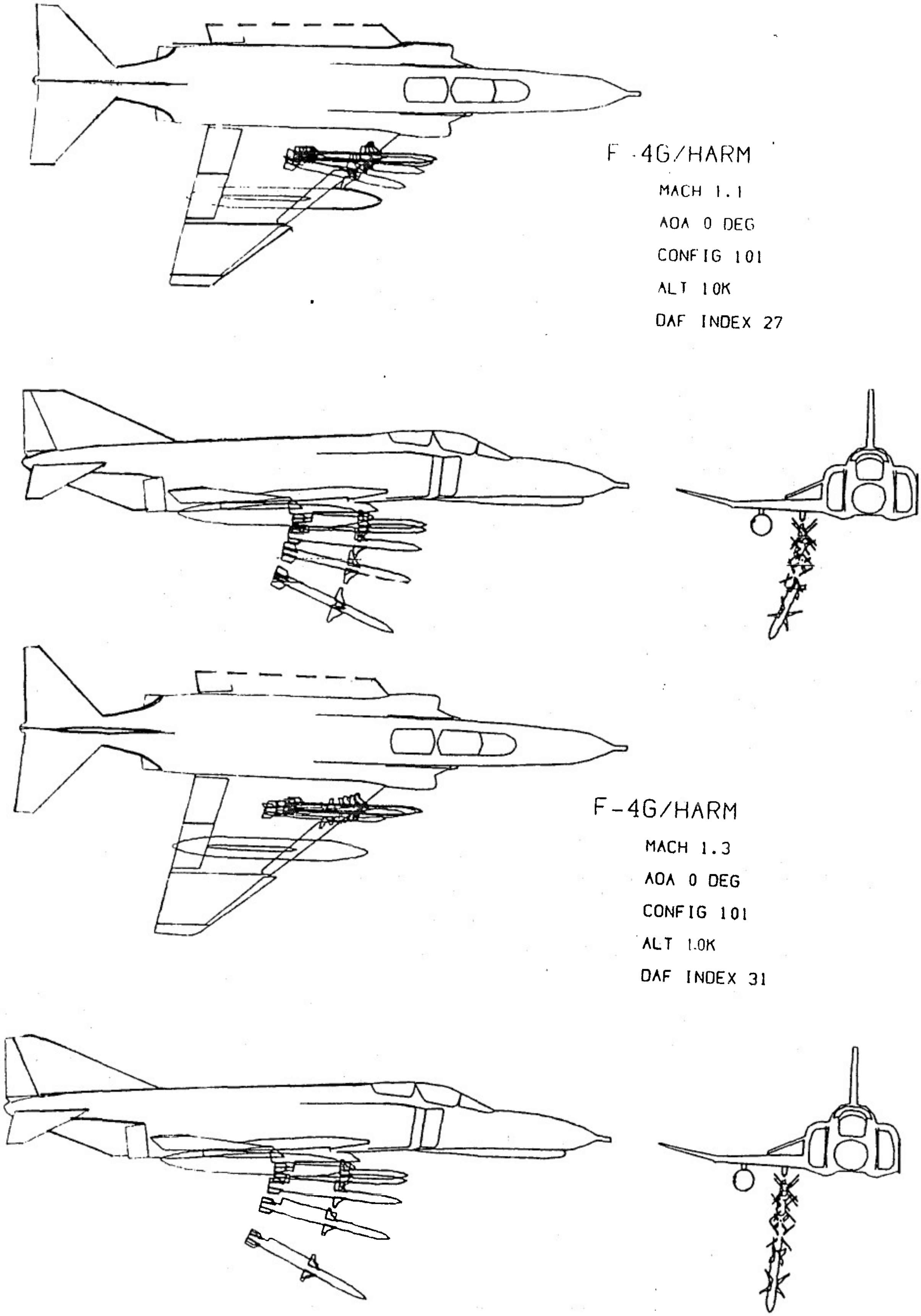


Figure 8b- Trajectory Simulations
(Config 101)

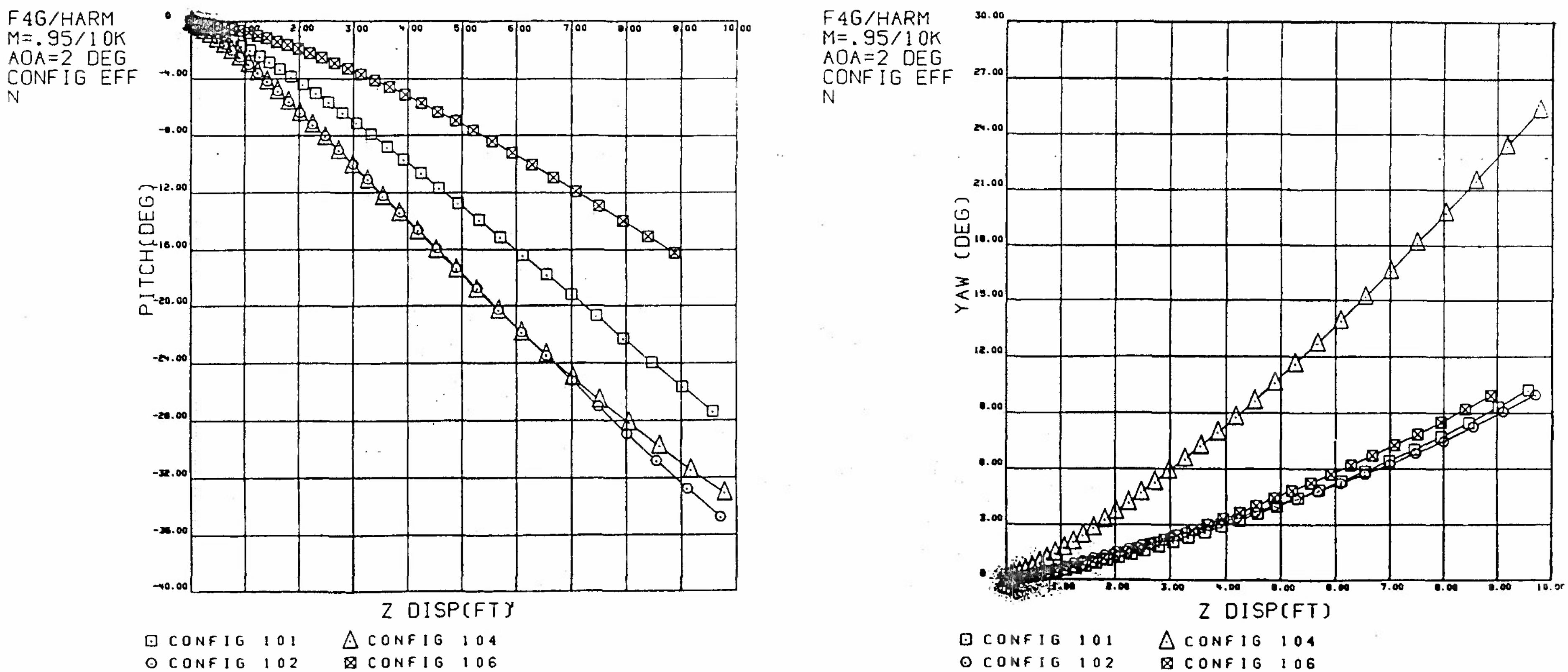


Figure 13a- Configuration Effects

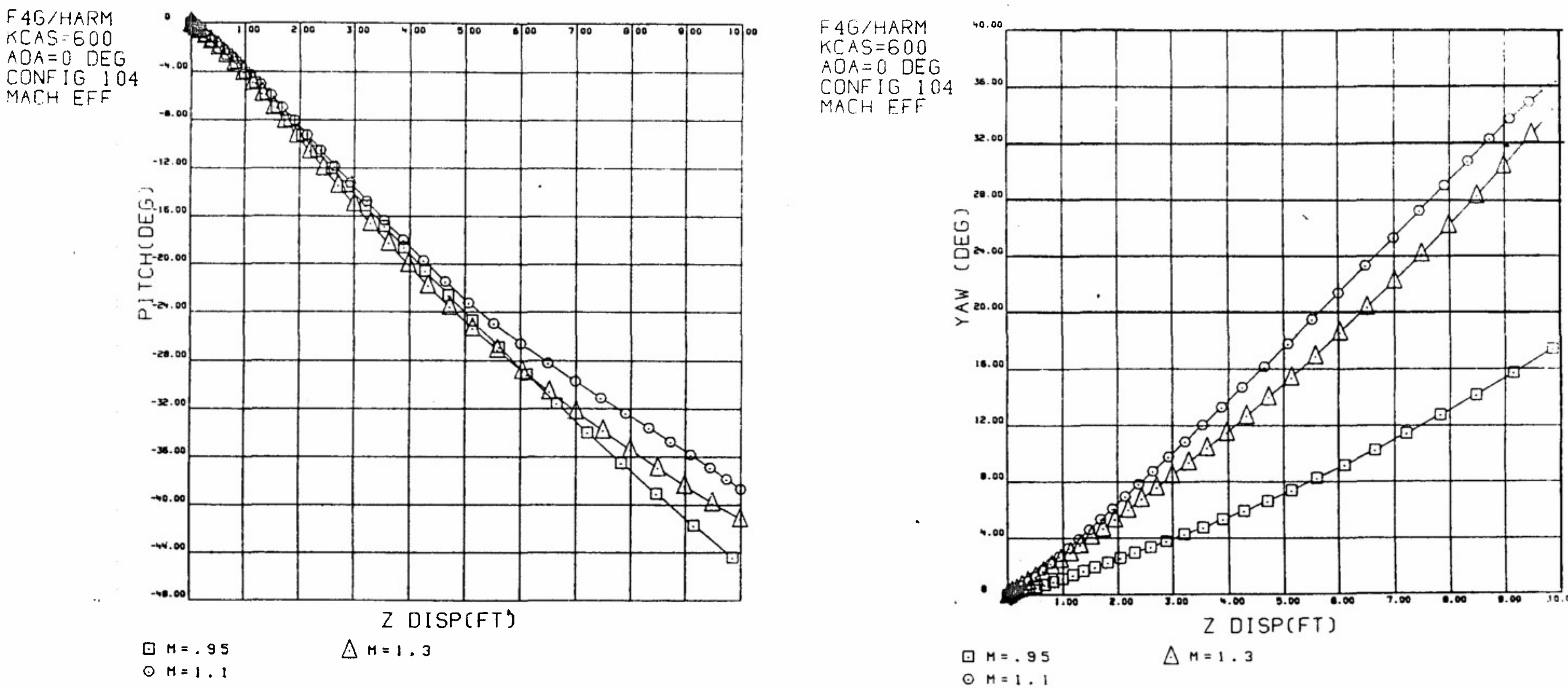


Figure 14c- Mach Number Effects

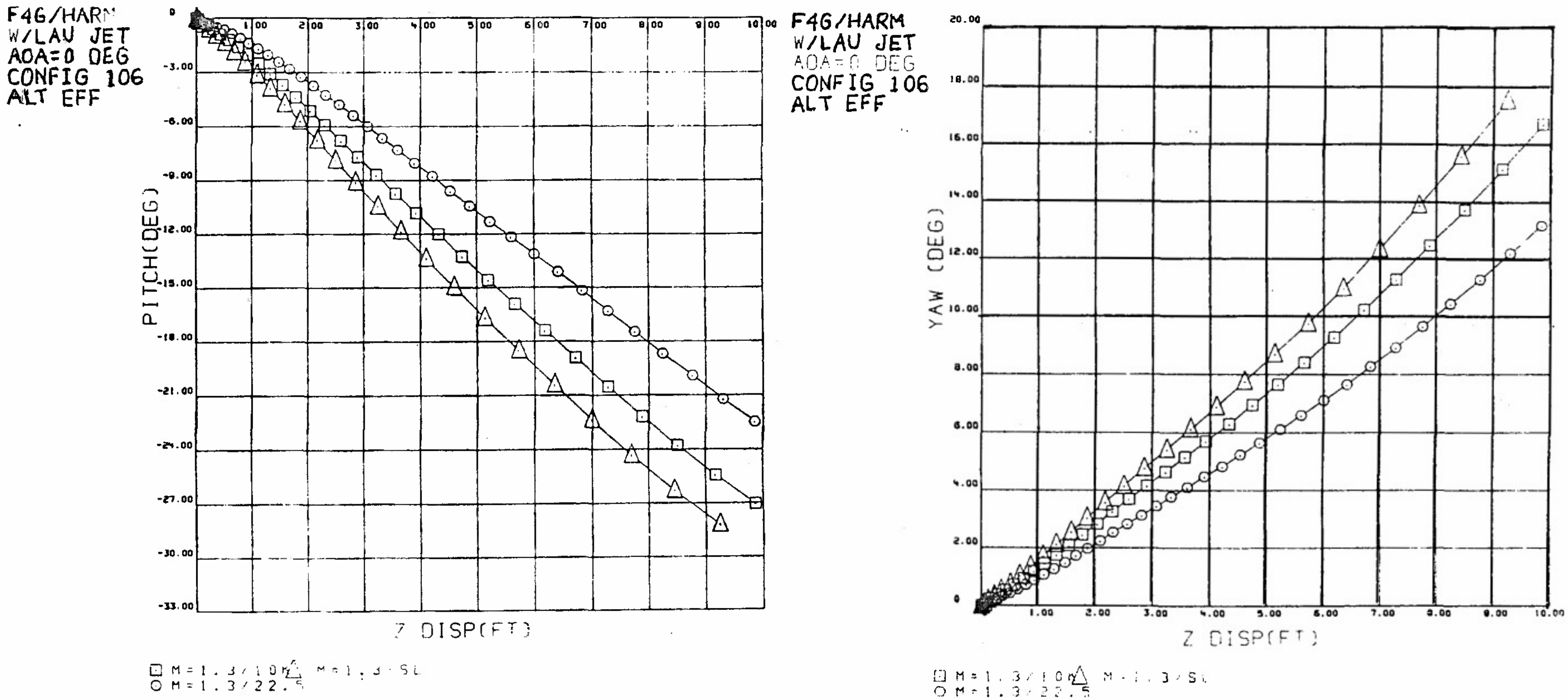


Figure 18b- Altitude/Dynamic Pressure Effects

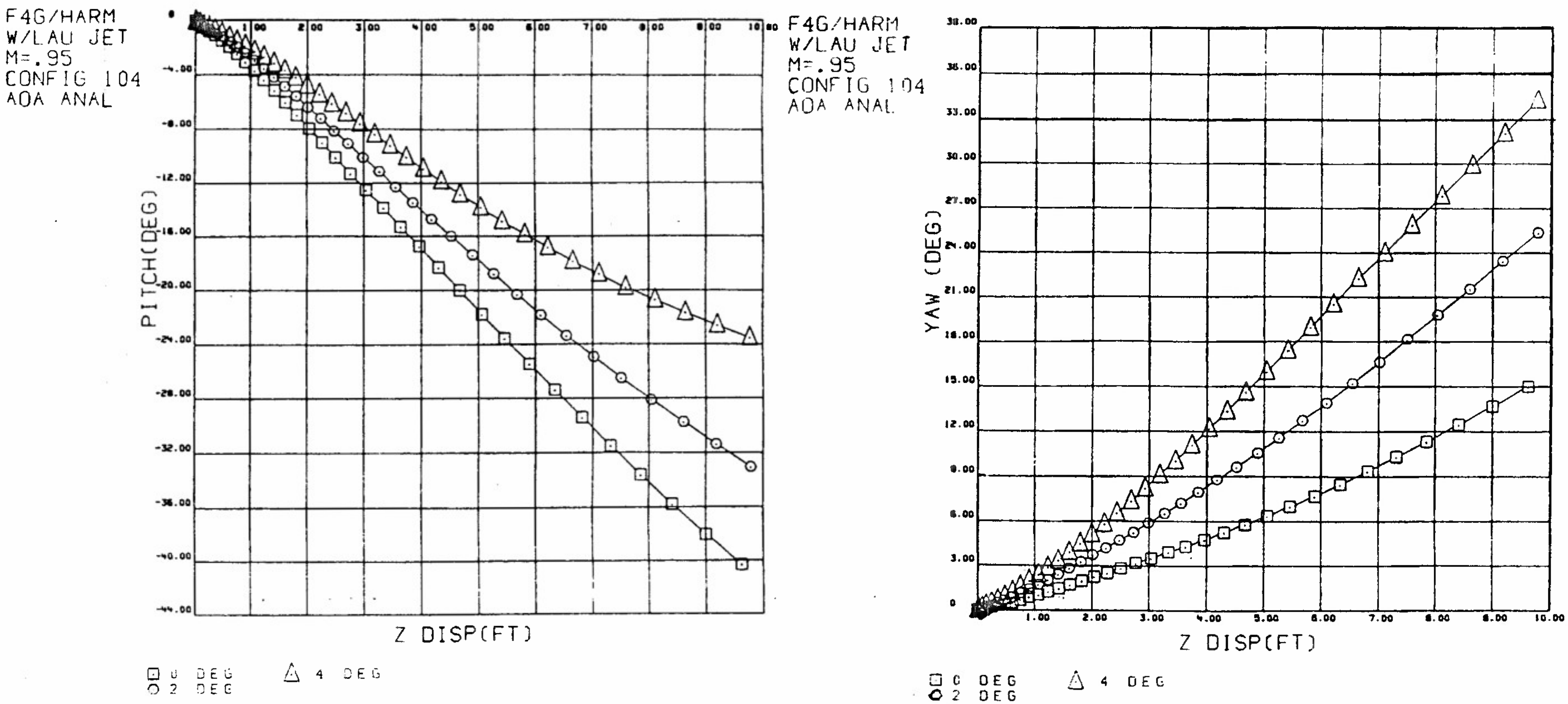


Figure 19c- Angle of Attack Effects

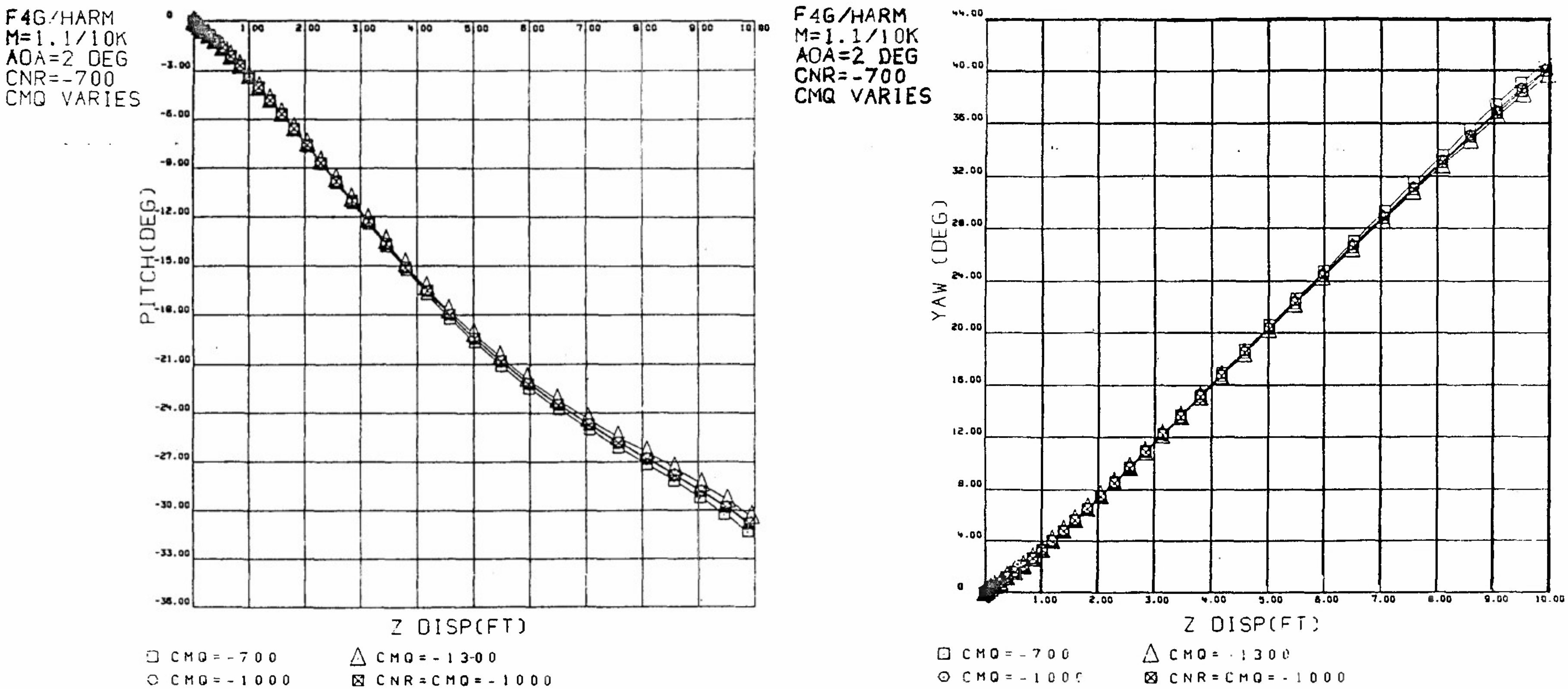


Figure 23c- Damping Derivative Effects

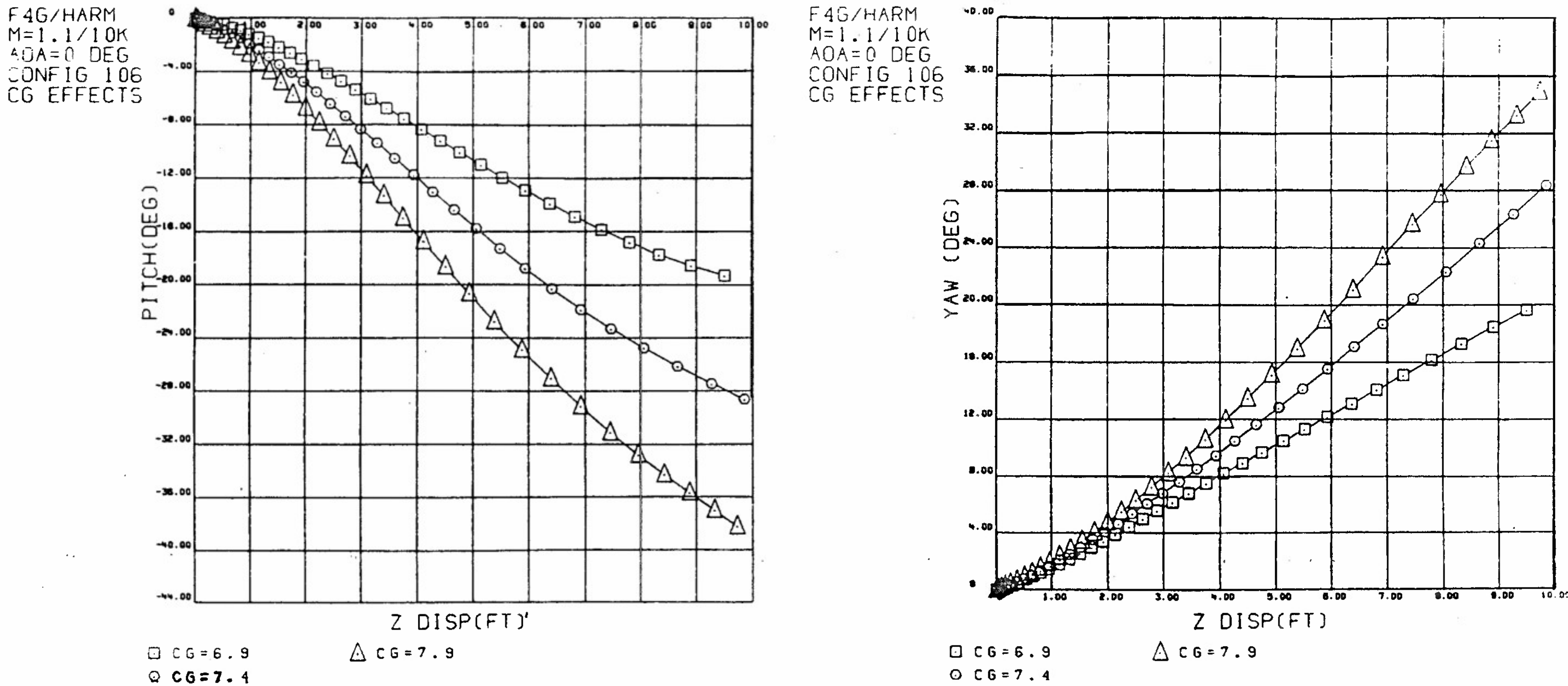
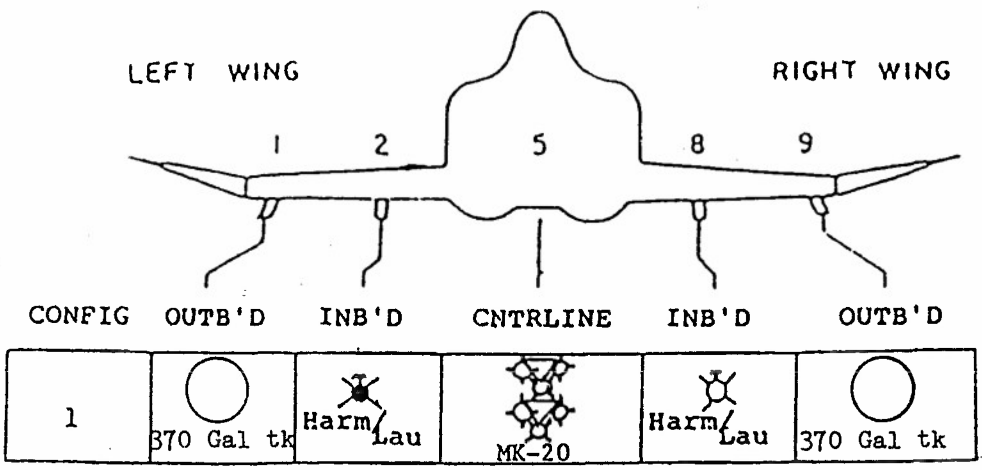


Figure 26d- Varying Mass Properties Effects



Configurations

CONFIG	MISSION	PASS	RELEASE	KCAS/MACH
1	1	1	P2	600/1.1
I	2	1	P2	650/1.3

Flight Profile

Figure 28

APPENDIX B

AERO MEMO 84-09

F-16/CBU-89 SEPARATION ANALYSIS

OFFICE FOR AIRCRAFT COMPATIBILITY
3246 TEST WING/TY

Eglin Air Force Base, FL 32548

OCTOBER 1984

NOTE: For the sake of brevity, only typical, representative, plots are included herein.

INTRODUCTION

BACKGROUND.

The F-16 SPO requested TY to support the TAC requirement for certification of the CBU-89 on the F-16 aircraft. The desired release limits for this weapon on the F-16 are: 600 KCAS/1.2 Mach on parent carriage and 550 KCAS/.95 Mach on multiple carriage.

PURPOSE.

The purpose of this memorandum is to analyze the CBU-89 separation characteristics and to prepare a flight test plan for an F-16/CBU-89 certification. This report will synthesize the data analysis accomplished in order to develop a flight test plan for store clearance. The test plan recommendation is also included in this document.

SCOPE.

The flight test recommendation will be based upon CBU-89 separation computer simulations. The configurations to be certified are shown in Figure 1. Figure 2 depicts drawings of the CBU-89, CBU-58 and MK-20 model used in the wind tunnel to gather free stream data. This data shows the aerodynamic similarities between the stores.

STORE CHARACTERISTICS.

The CBU-89 is a cluster munition which enters a spin mode after release, using centrifugal force to disperse submunitions. This spin mode, activated by canting the deployed tail fins, occurs after the store has fallen clear of the aircraft. The rotating tail fins open within 150 ms after release and will, therefore, be taken into consideration with respect to the separation analysis. However, because of the timing of the spin mode, the cant of the fins will not be considered in the analysis. Mass properties of the CBU-89 are listed in Table 1.

FREE STREAM CHARACTERISTICS.

Although TYE has not conducted a wind tunnel test with the CBU-89, free stream data for the store is available through the Free Stream Data Retrieval System. By studying the mass and physical properties of the CBU-89, an engineering assessment is that this store has a combination of the characteristics of the CBU-58 and the MK-20. In particular, the CBU-89 is similar in size and weight to the CBU-58 and resembles a MK-20 shape. In order to depict how the CBU-89 is analogous to the combined characteristics of these two stores, Figures 3 and 4 show example plots of the normal force and pitching moment coefficients versus store angle of attack. All data are for closed fins and consistent store orientation.

The same comparison was conducted using open fins configuration. See Figures 5 and 6. This time only CBU-58 and CBU-89 were plotted. As seen by the plots, the CBU-89 has fins closed free stream characteristics in the transient range between the CBU-58 and the MK-20. Nevertheless, for the fins-open configuration, the CBU-89 is shown to be more stable than the CBU-58.

The next section will discuss the separation characteristics of the CBU-89 using CBU-58 interference coefficients.

APPROACH.

The Six-Degree-of-Freedom grid simulation program was used to generate the trajectories presented on this analysis. In this program, total coefficients were derived from the CBU-89 free stream data combined with interference data from CBU-58. This last data was collected during wind tunnel test TC-524 conducted by AEDC in PWT/4T (AEDC-DR-78-42). Trajectories are depicted as three view drawings of the store as it separates from the aircraft. All separations are shown as right wing releases. The CBU-89 separations analysis simulated releases from a parent pylon on stations 3 and 7. In addition, simulated releases from TERs on stations 3, 4, 6 and 7. Table 2 shows the ejector forces and moments used in the Six-Degree-of-Freedom program.

PREVIOUS FLIGHT TEST.

The CBU-89 was previously released on the F-16 aircraft. It is documented in AD-TR-83-32. This test evaluated single carriage and release of the CBU-89 on pylon stations 4 and 6. The release conditions for these were as follows: airspeeds between 529 and 695 KTAS; altitudes from 1,830 to 15,770 feet AGL; and dive angles up to 60 degrees. It also evaluated multiple carriage and release (slant 4 configurations) of the CBU-89 from TERs on pylon stations 4 and 6 of the F-16 with centerline fuel tank. The release conditions tested for this configuration ranged from 9,250 to 12,000 feet AGL in altitude, 525 to 610 KTAS, and 30 to 60 degree dive angle. Ripple release for slant 4 configuration was performed at 70 and 300 millisecond intervals.

SIMULATION RESULTS.

The CBU-89 simulations were conducted on parent carriage and multiple carriage configurations. Figure 1 shows the configurations simulated. The altitude range on the simulation was from 1,000 feet to 20,000 feet. Similarly, the Mach number was varied from .6 to 1.2 for parent carriage and from .6 to .95 for multiple carriage.

AOA was varied from 0 to 6 degrees on all simulation configurations.

By using the altitude and Mach number variations, the simulation was built up to the desired goal of 600 KCAS/1.2 Mach on parent carriage and 550 KCAS/.95 Mach on multiple carriage. These simulations were conducted at 0 degree and 60 degree dive angles. The results are shown in Figures 38 through 47. A center of gravity (C.G.) sensitivity analysis was also conducted to investigate store stability. Figures 8 through 37 are examples of the CBU-89 pictorial and graphical views of the store's separation which were generated by the Six-Degree-of-Freedom program.

a) Configuration Effects.

(1) For all simulated conditions and configurations, the CBU-89 showed safe separation characteristics.

(2) For releases from outboard shoulder on inboard pylon, the store tended to translate outboard at lower speeds but tended to translate inboard for higher speeds.

b) Mach Effects.

(1) For all conditions and configurations simulated, an increase in speed for the same angle-of-attack tended to slightly increase Z-translation and negative pitch. Yawing was not significant enough to cause any concern about collisions.

(2) As a general rule, the trajectories became more perturbed as the Mach number increased.

c) Aircraft Angle-of-Attack.

For all configurations, an increase in angle-of-attack for the same conditions tended to slightly increase the CBU-89s pitch and yaw; it also decelerated the store's Z-translation.

d) The C.G. sensitivity analysis illustrated in Figures 38 through 47 shows very little change in the separation characteristic of the store.

e) The dive angle analysis illustrated in Figures 48 through 57 indicates no significant change in separation characteristics.

SUMMARY.

a) This analysis demonstrated the separation characteristics of the CBU-89. Due to lack of wind tunnel data, interference coefficients from the CBU-58 were utilized to conduct the CBU-89 simulations. A comparison of free stream data for both fins-closed and fins-open configurations, and the fact that both stores are very similar, justified the use of CBU-58 interference data in conjunction with CBU-89 free stream data for the analysis. In general, all simulations showed safe separations. An increase in Mach number for constant AOA slightly increased the pitch rate, Z-translation and yawing moment. An increase of AOA for constant Mach number increased the pitch and yaw but decelerated the store's Z-translation. The C.G. sensitivity analysis indicated no significant effect on separations.

b) The 60 degree dive angle release indicated very little effect on the store's separation characteristics.

c) A review of AD-TR-83-32 corroborates the safe separation predictions. This report includes flight test information on CBU-89 releases from the F-16 aircraft.

d) Film review of previously released CBU-89 and CBU-58 stores from the F-16 aircraft were conducted. These show the same separation characteristics as those simulated in this analysis.

FLIGHT TEST RECOMMENDATIONS.

Due to the safe separation characteristics exhibited by the CBU-89 from the F-16 aircraft, the following release demonstrations are recommended (see Figure 7):

MISSION	PASS	RELEASE	KCAS/MACH	DIVE	CONF.
1	1	Pylon 3	500/.95	-60	1
2	1	Pylon 3	550/1.05	-60	1
3	1	Pylon 3	600/1.2	-60	1
4	1	Pylon 3 TER/1	550/.95	-60	2
4	2	Pylon 3 TER/2	550/.95	-60	2
5	1	Pylon (3-7) Ripple Pair Release (70ms)	550/.95	-60	3
6	1	Pylon (3,4,6,7) Ripple Pair Release (70ms)	550/.95	-60	3

TABLE 1

CBU-89 MASS AND PHYSICAL PROPERTIES

WEIGHT (lbs.)	680 $\pm$ 5%
LENGTH (ft.)	7.67
DIAMETER (in.)	15.60
FWD MOUNTING LUG (in-aft of nose)	35.00
CG (in-aft of fwd lug) (ins.)	7.6 $\pm$ 0.5
MOMENTS OF INERTIA	
Ixx (slug - ft^2)	4.40
Iyy (slug - ft^2)	83.20
Izz (slug - ft^2)	83.20

TABLE 2

FORCES AND MOMENTS USED FOR THE CBU-89 SIMULATIONS
(Inputs in the Six-Degree-of-Freedom)

CONF.	PARENT CARRIAGE	CHIN STATION	SHOULDER STATION
* 602	EFORCZ = 7233 LBf EMOMY = 1501 FT • LBf		
402		EFORCZ = 1200 LBf EMOMY = 140 FT LBf	
502			EFORCZ = 848.4 LBf EFORCY = 848.4 LBf EMOMY = 99.0 FT • LBf EMOMZ = -99.0 FT • LBf
601		EFORCZ = 1200 LBf EMOMY = 140 FT. LBf	
701			EFORCZ = 848.4 LBf EFORCY = 848.4 LBf EMOMY = 99.0 FT • LBf EMOMZ = -99.0 FT • LBf

* Cartridges and orifice combination

ARD-863/ARD-446
.081/.110 (inches)

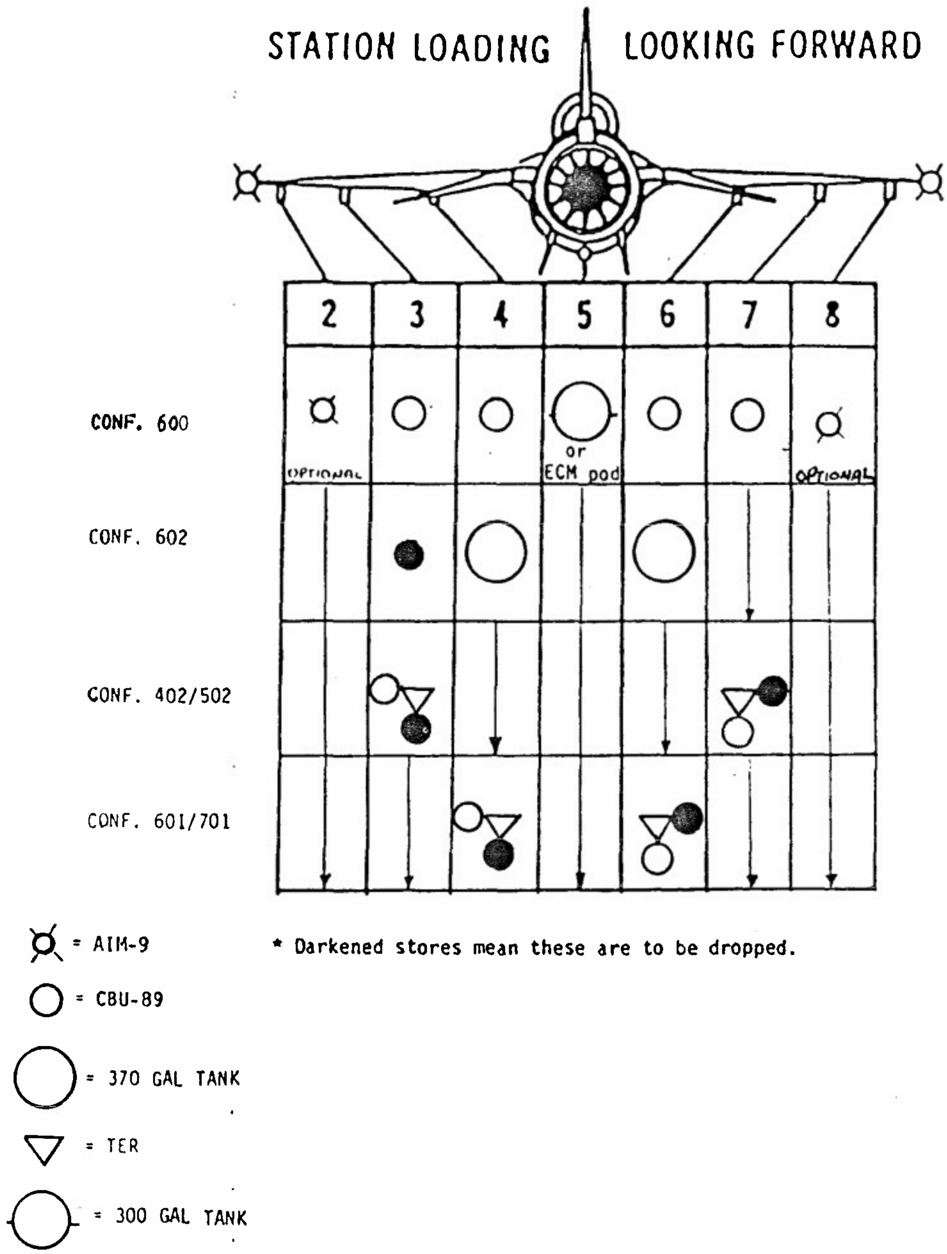
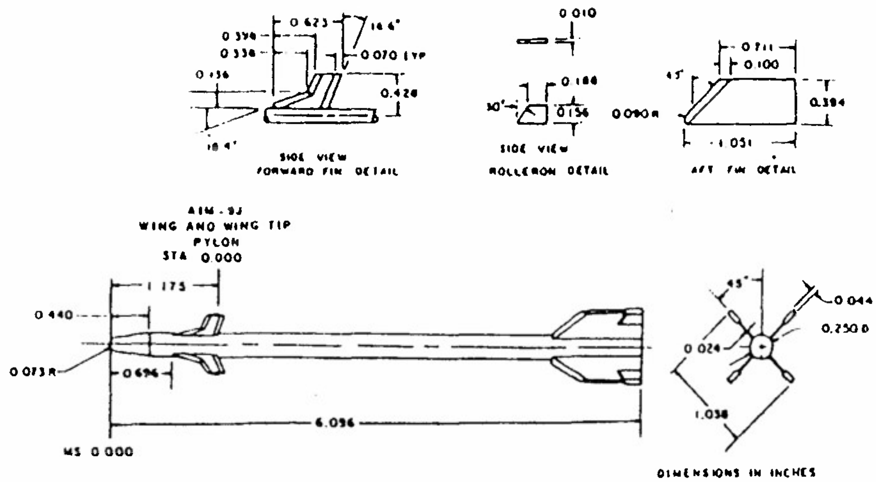
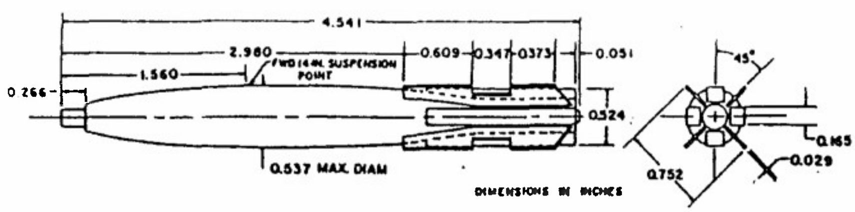

STATION LOADING
LOOKING FORWARD
2
3
4
5
6
7
8
CONF. 600
OPTIONAL
or
ECM pod
OPTIONAL
CONF. 602
CONF. 402/502
CONF. 601/701
= AIM-9
= CBU-89
= 370 GAL TANK
= TER
= 300 GAL TANK
* Darkened stores mean these are to be dropped.

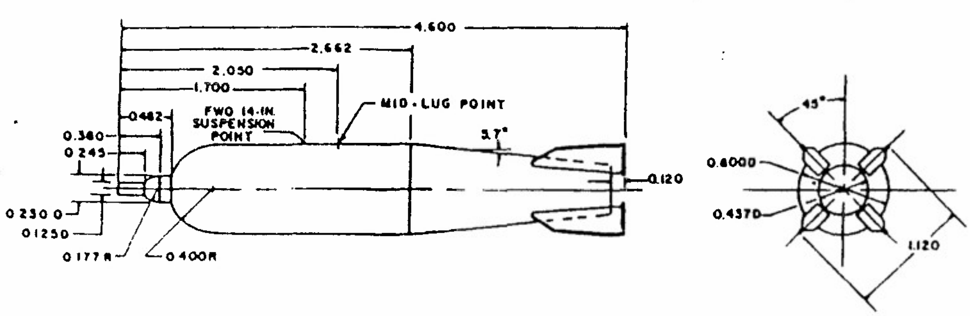
Figure 1



AIM-9J

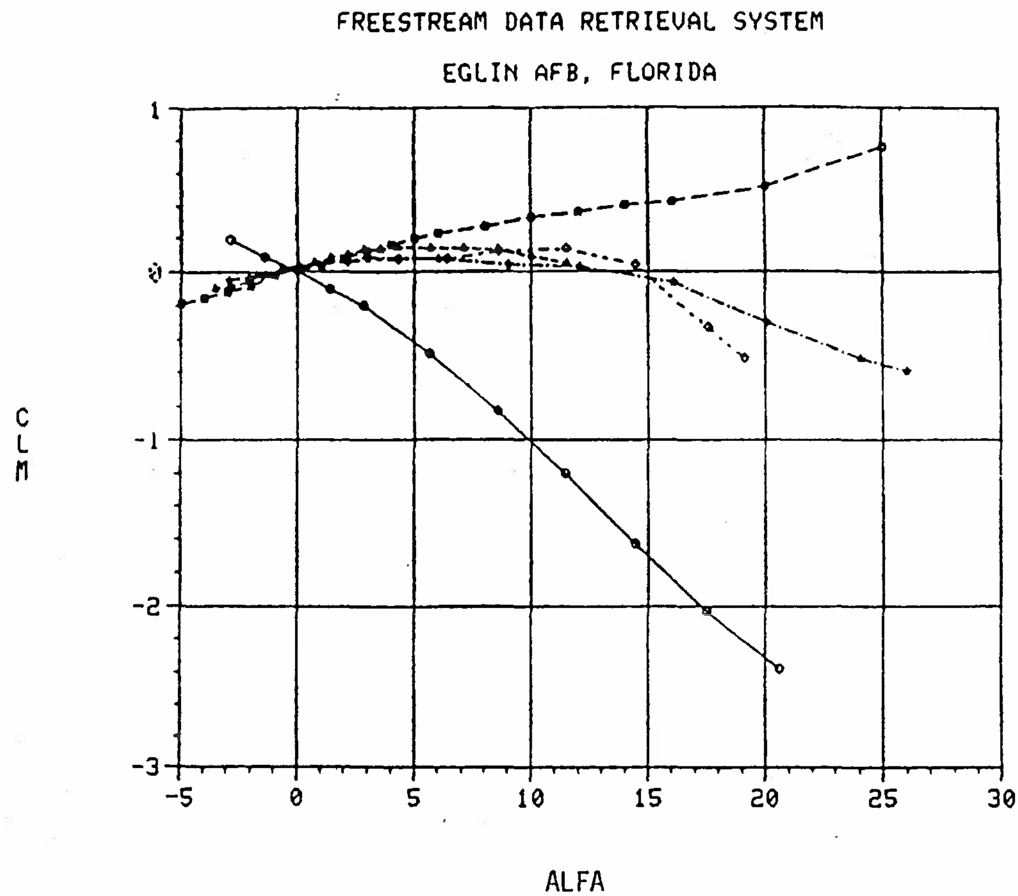


MK-82SE



CBU-58A/B

Figure 2-Wind Tunnel Models



SYMBOL & LINE	RECORD NUMBER	DATA SET#	X-VARIABLE DATA NAME	Y-VARIABLE DATA NAME	
⊖———⊖	29	1	ALFA	CLM (CBU-58(+)	M=.60)
△-----△	18	2	ALFA	CLM (MK-20(+)	M=.80)
□— — —□	18	1	ALFA	CLM (MK-20(X)	M=.80)
★-·-·-★	35	72	ALFA	CLM (CBU-89(X)	M=.70)
◇-----◇	35	73	ALFA	CLM (CBU-89(+)	M=.70)

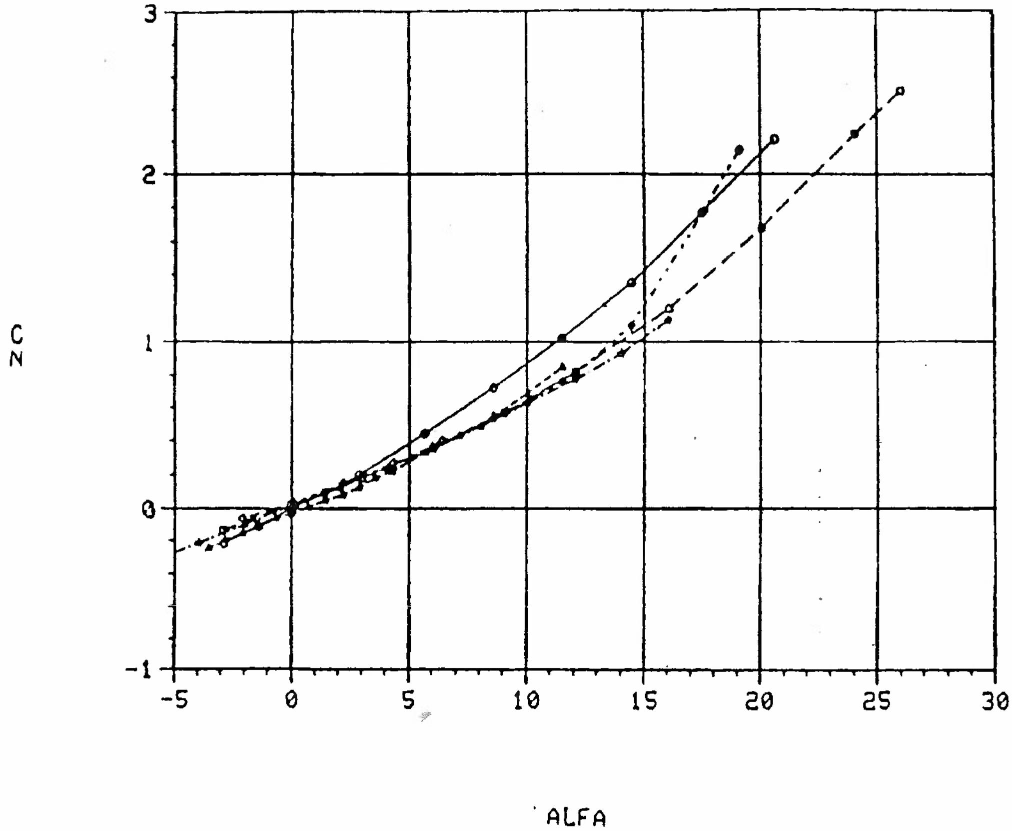
DOTTED LINES WITH SYMBOLS AT THE ENDS ARE CURVE FITS.

(+) - Fins at 0 deg
(X) - Fins at 45 deg

Figure 3- Pitching Moment vs Store Angle of Attack

FREESTREAM DATA RETRIEVAL SYSTEM

EGLIN AFB, FLORIDA



SYMBOL & LINE	RECORD NUMBER	DATA SET#	X-VARIABLE DATA NAME	Y-VARIABLE DATA NAME	
○————○	29	1	ALFA	CN (CBU-58(+)	M=.60)
△- - - - - -△	18	2	ALFA	CN (MK-20(+)	M=.80)
□— — — —□	35	72	ALFA	CN (CBU-89(X)	M=.70)
★-·-·-·-·-★	50	127	ALFA	CN (MK-20(X)	M=.70)
◇- - - - - -◇	35	73	ALFA	CN (CBU-89(+)	M=.70)

DOTTED LINES WITH SYMBOLS AT THE ENDS ARE CURVE FITS.

(+) - Fins at 0 deg

(X) - Fins at 45 deg

Figure 4- Normal Force vs Store Angle of Attack

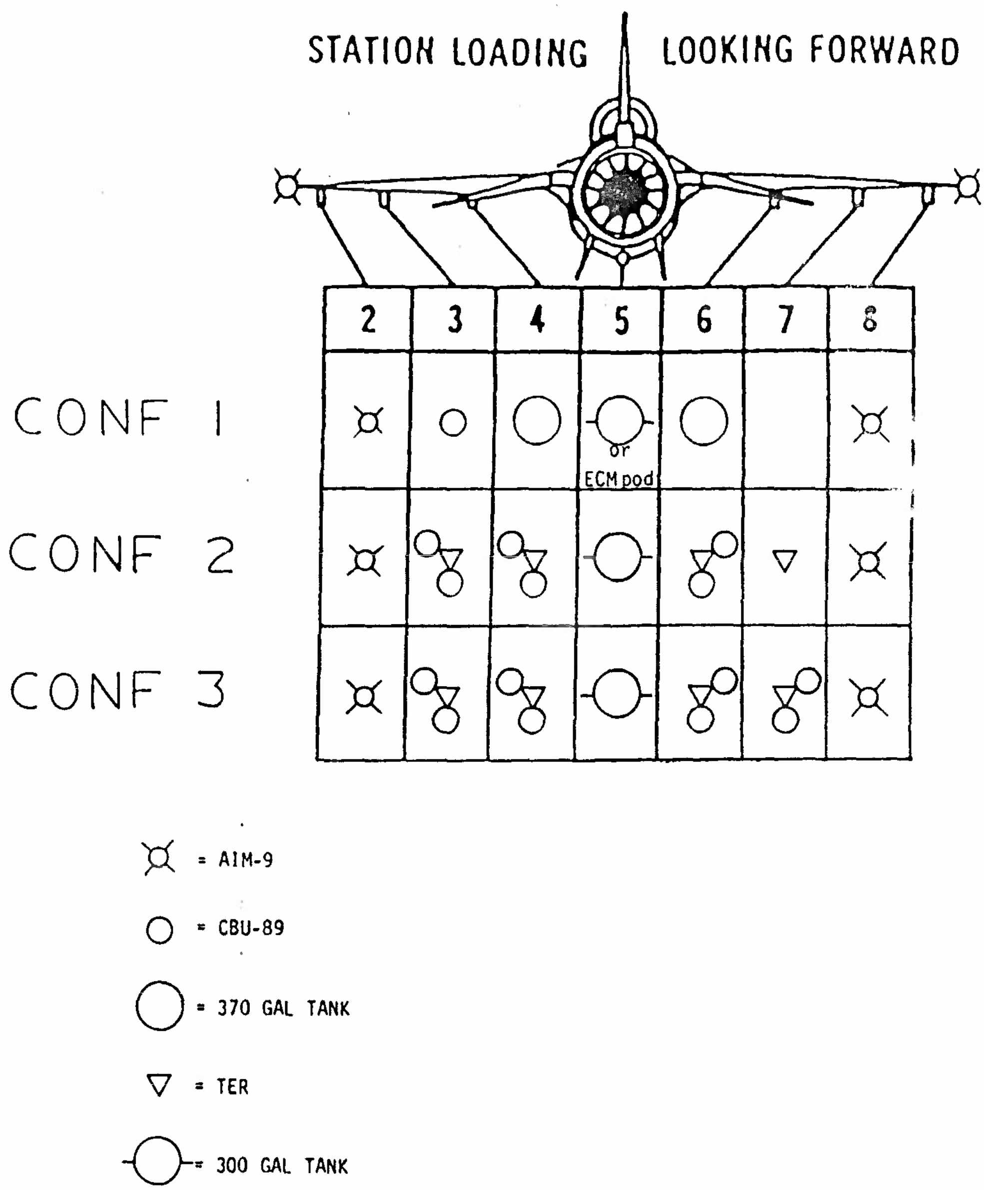


Figure 7. Flight Test Configurations

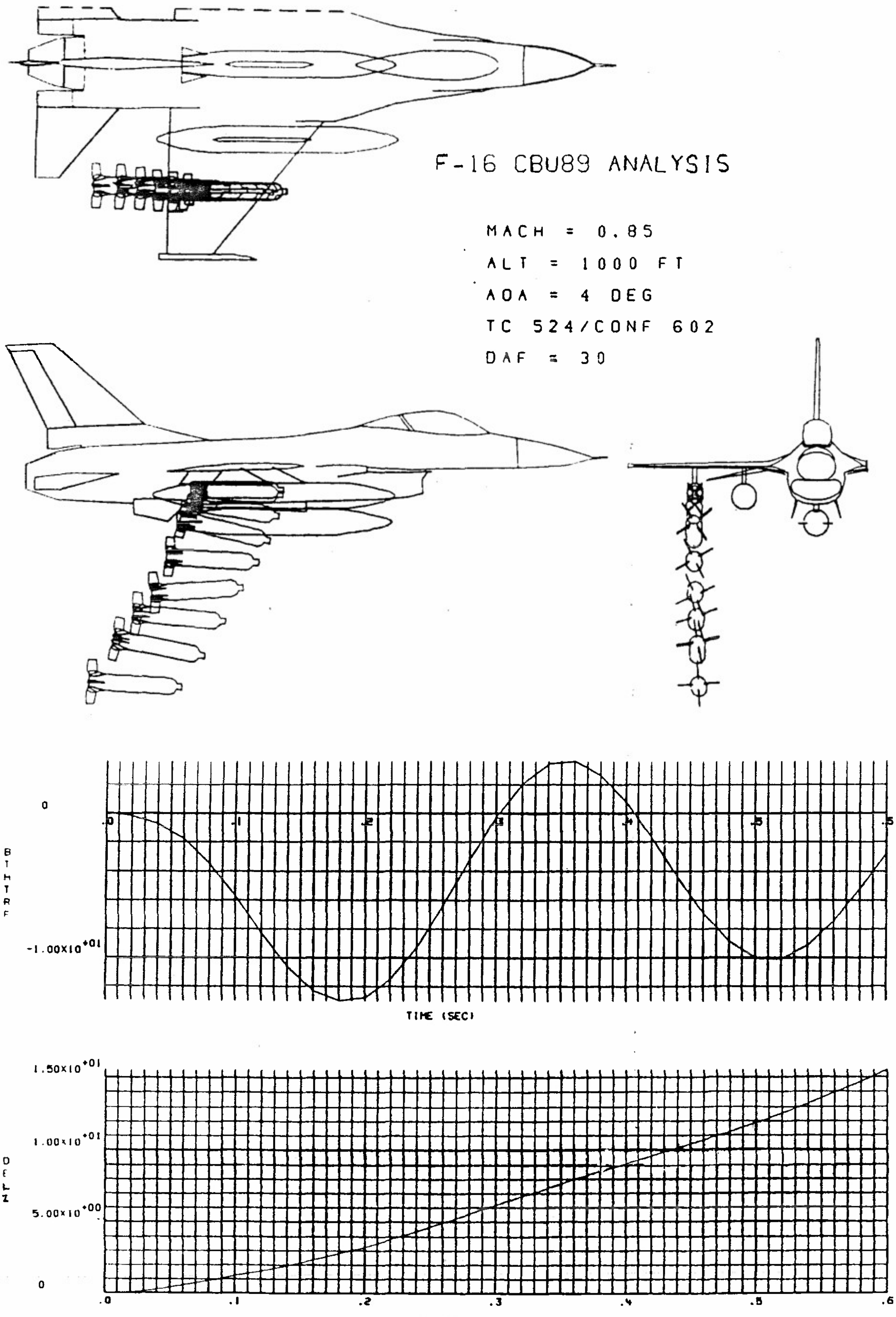

F-16 CBU89 ANALYSIS
MACH = 0.85
ALT = 1000 FT
AOA = 4 DEG
TC 524/CONF 602
DAF = 30
BTHTRF
0
-1.00x10+01
.0
.1
.2
.3
.4
.5
.6
TIME (SEC)
DELZ
1.50x10+01
1.00x10+01
5.00x10+00
0
TIME (SEC)

Figure 10

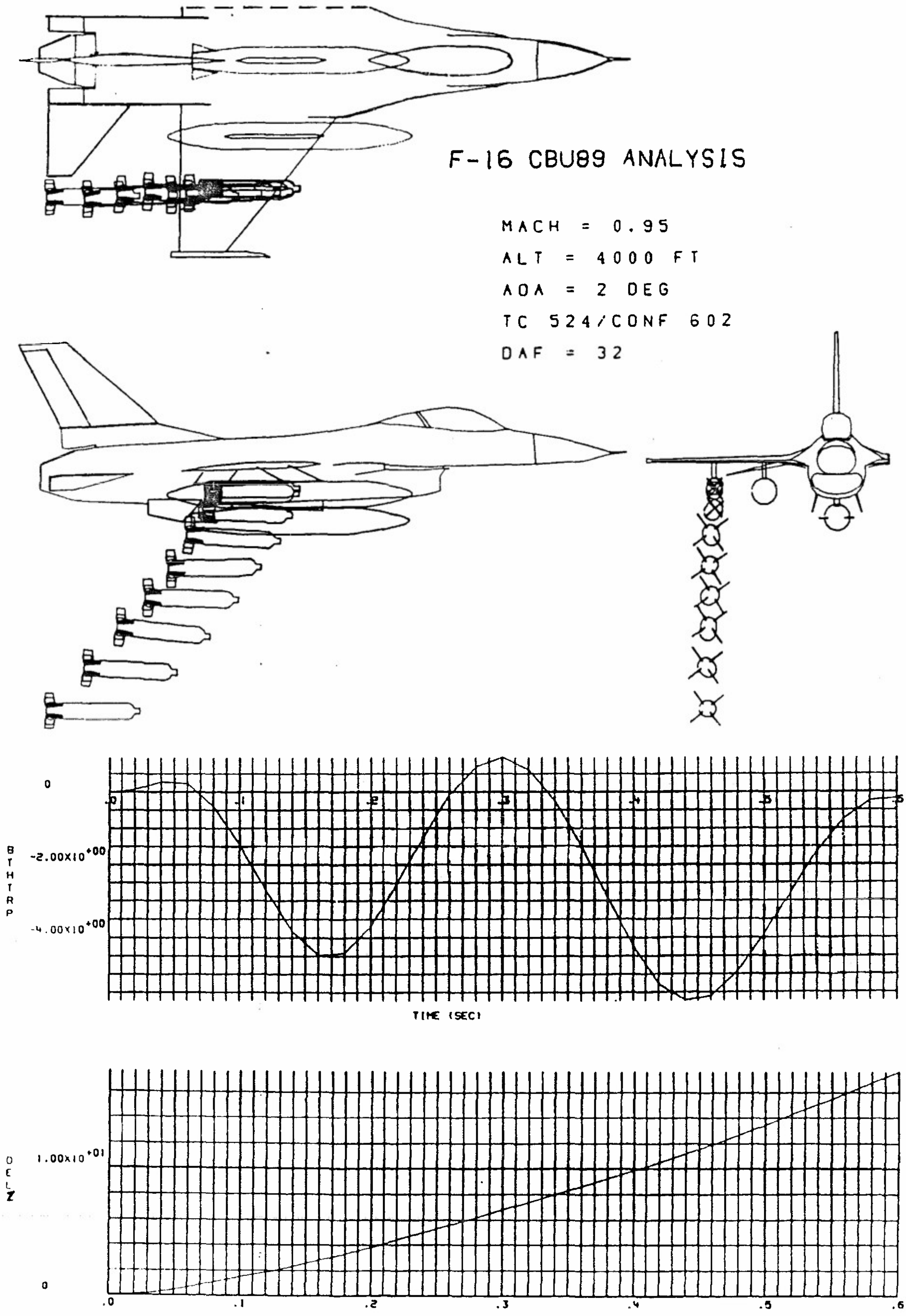

F-16 CBU89 ANALYSIS
MACH = 0.95
ALT = 4000 FT
AOA = 2 DEG
TC 524/CONF 602
DAF = 32
BTHTRP
0
$-2.00\times10^{+00}$
$-4.00\times10^{+00}$
.0
.1
.2
.3
.4
.5
.6
TIME (SEC)
DELZ
$1.00\times10^{+01}$
0
.0
.1
.2
.3
.4
.5
.6
TIME (SEC)

Figure 12

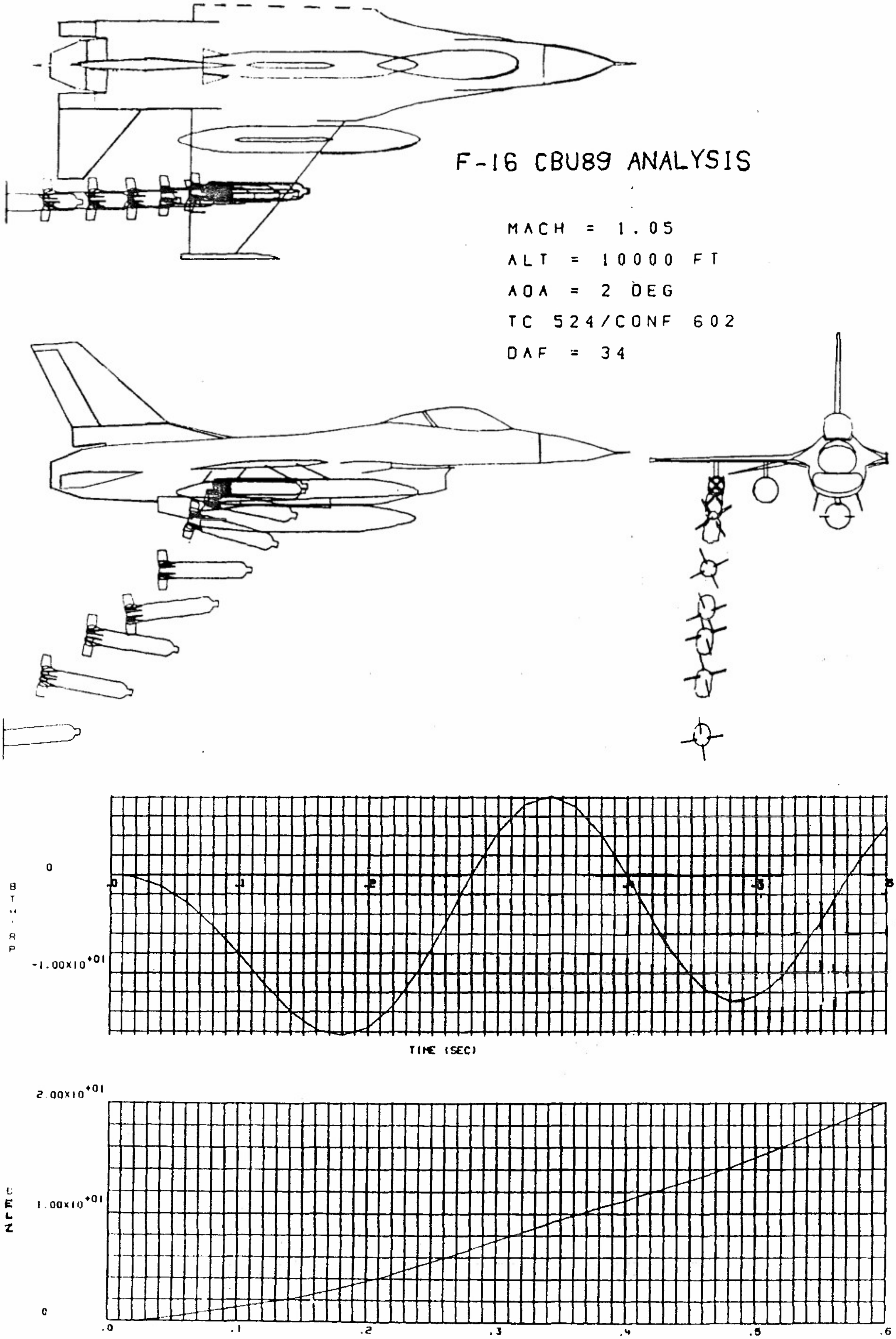

F-16 CBU89 ANALYSIS
MACH = 1.05
ALT = 10000 FT
AOA = 2 DEG
TC 524/CONF 602
DAF = 34
0
-1.00x10+01
TIME (SEC)
2.00x10+01
1.00x10+01
0
.0
.1
.2
.3
.4
.5
.6

Figure 14

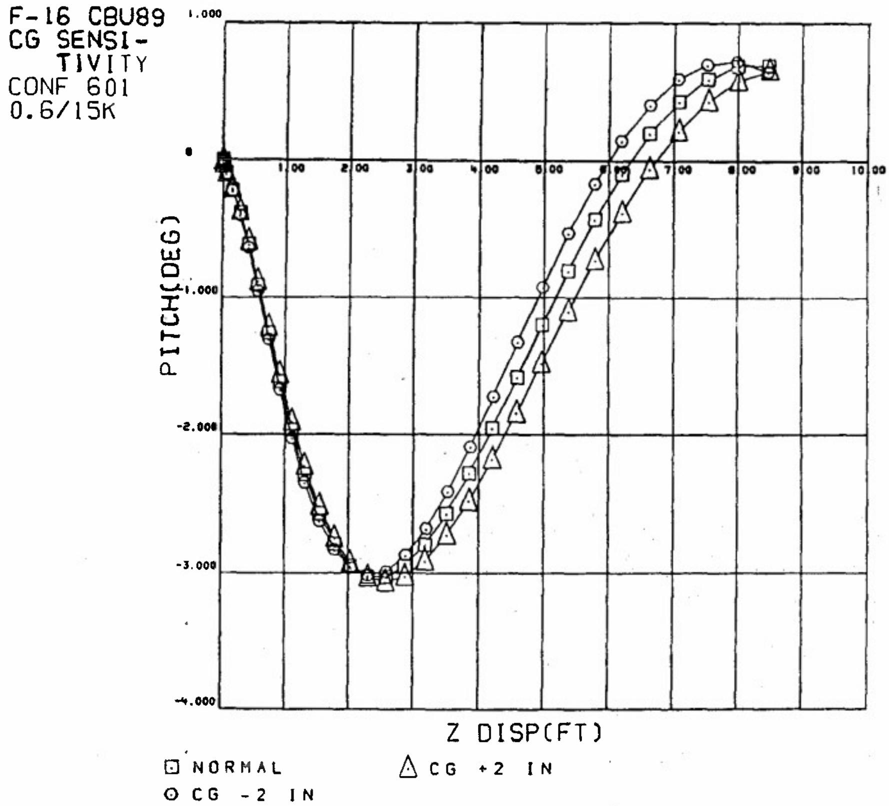


Figure 44

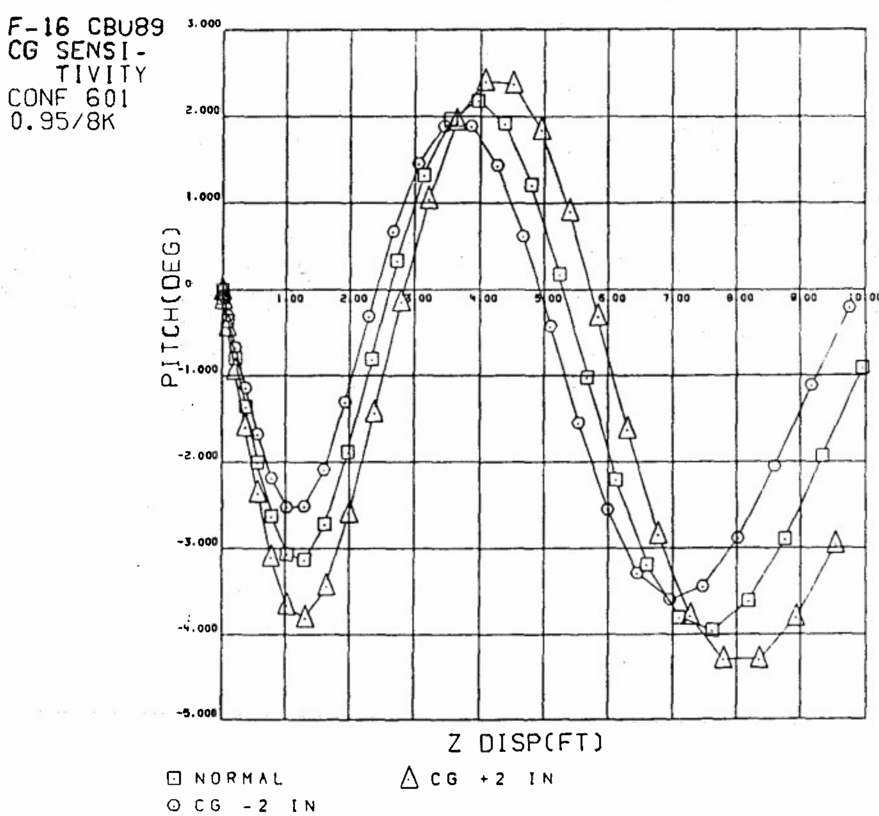


Figure 45

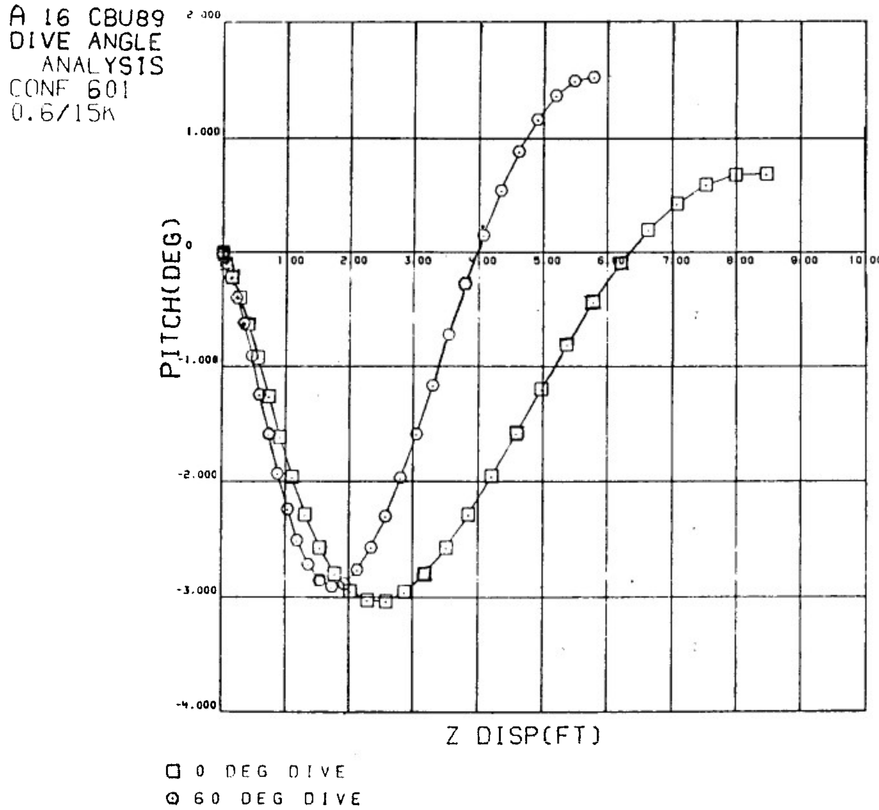


Figure 54

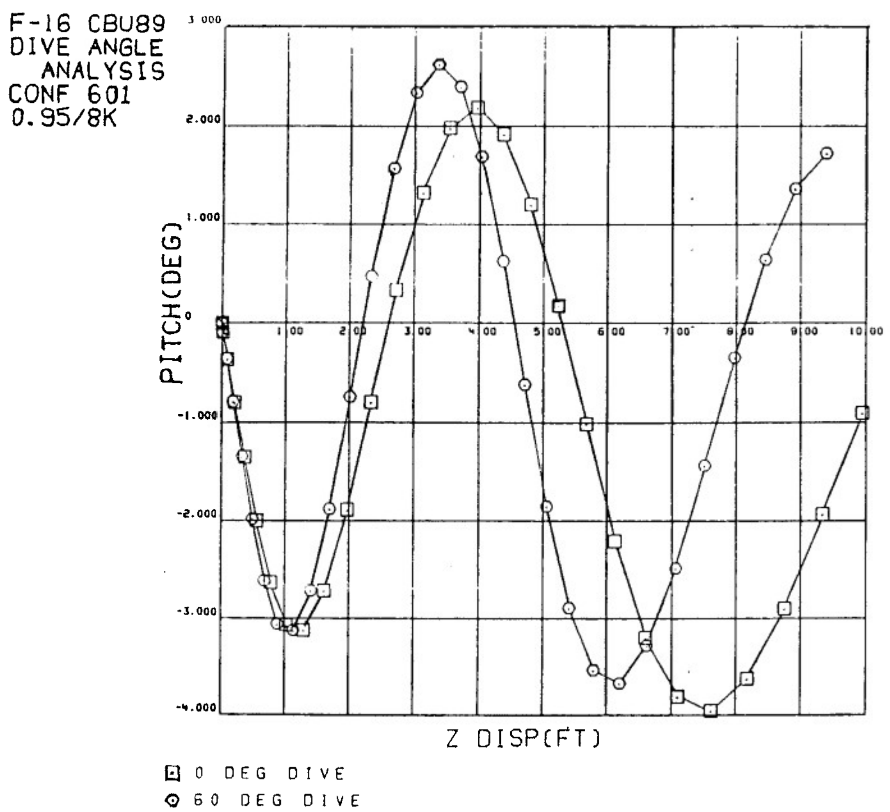


Figure 55

APPENDIX C

GRAPHIC ATTITUDE DETERMINING SYSTEM

OFFICE FOR AIRCRAFT COMPATIBILITY

3246 TEST WING/TY

Eglin Air Force Base, FL 32542

APRIL 1984

NOTE: For the sake of brevity, only typical, representative, plots are included herein.

GRAPHIC ATTITUDE DETERMINING SYSTEM

GENERAL

The Graphic Attitude Determining System (GADS) is a computer based system for collecting and reducing stores separation data from 16mm film. The system converts the film image to video, mixes it with a video display generated by the computer, and presents the superimposed images on a video monitor. The operator then commands the computer to align the images at which point the location of the store is known. The hardware was delivered by DBA Systems Inc. in accordance with a detailed specification written by AD/KRE, Eglin AFB, FL. All software was written in-house by J. Kocanowski and M.A. Smith.

METHDD

All methods of stores separation data reduction, which uses single cameras, are based on the same principle. Specifically, they make use of the fact that distance information is encoded in the film image as apparent distortion of the image due to perspective. This "distortion" exists because as an object moves farther from the camera it subtends a smaller angle within the total field of view of the camera. This in turn causes the object to appear to shrink toward the optical center of the camera with increasing viewing distance. The amount of "distortion" of the image is related not only to the distance but also the focal length of the camera lens. That is, shorter focal length lenses (wider field of view) increase the perspective while long focal length lenses (telephoto) flatten out the image. By knowing the focal length of the lens and the precise positional relationship between several fixed points on the store it is possible to retrieve this distance information. With sufficient points it is possible to resolve the data into the six degrees of freedom required to characterize the separation of the store.

The photogrammetric method uses precisely painted spots on the surface of the store as reference points. These spots are then measured within each frame of film. The data from the store prior to separation is then used to locate the position of the camera with respect to the store. The later frames can then be reduced with respect to the camera and then translated and rotated back to the coordinate system of the store prior to release.

The Photo Data Analysis System (PADS) developed at the Naval Missile Center located at Point Mugu, CA does away with the need for painted spots. Instead an exact model of the store is placed on a mechanical positioning system. The model is then viewed with a video camera using the same lens that was used on the airborne camera. Doing so duplicates the amount of perspective in the image and thus eliminates focal length as a variable. The video is then mixed with a video image of the film and the superimposed images are then displayed on a video monitor. The operator then moves the model, using the positioning system, to obtain a precise match of the two images. The position of the model can then be recorded and later scaled to obtain the actual position of the store.

The GADS uses a computer to generate a video image of the outline of the store. This video is then mixed with a video image of the film and displayed on a video monitor. An operator then supplies commands to the computer to move the image of the store until the two images are aligned. To make this possible the computer must calculate the amount of perspective, based on the location of the store with respect to the camera, and distort the image by an appropriate amount. To do so the computer must know the characteristics of the camera.

EQUIPMENT

In early 1978, a specification for the GADS was developed by the System Engineering Branch of the Directorate of Computer Sciences at Eglin AFB. This specification was based in part on a feasibility study which had been performed by S. Walters. During the study, Mr Walters wrote a program for the IBM-36D to display an image of a store on a Vector General display. Positioning of the image was controlled through a function keyboard. A 16 mm movie projector was then used to project frames of film directly on the face of the display. The computer generated image was then moved to achieve superposition. The data collected during the test compared very well with the data resulting from the photogrammetric solution and therefore indicated that the basic method was feasible.

While conducting the feasibility study, one problem area became very apparent. This concerned control of the computer image. The method that had been used was to use function keys to start, stop, and change the direction of motion of the image in its six degrees of freedom. While this was not a problem in X, Y, and Z, it was very difficult to control roll, pitch and yaw. Specifically, it was very difficult for the operator to relate use of the controls to the direction that he wanted to rotate the store in. This was compounded by the fact that if, for example, the store were to yaw such that it points in the opposite direction, then the roll and pitch controls reverse direction. That is, a motion of the control which used to cause pitch up, now causes pitch down. It was apparent that using joysticks as had been planned would not be much better for contolling the rotations. Based largely on ideas formulated by V.G. Clements, the design for the special purpose attitude control shown in Figure 1 took shape. In this design the rod represents the store with one end designated as the nose and other as the tail. This rod is free to rotate approximately plus or minus 30 degrees on each of three axes. These three movements supply three analog voltage levels to the computer which are then interpreted as rotation commmands about the three axes. Each axis is spring loaded to cause it to return to its zero position when the operator releases it. This allows the attitude control to be used as a velocity rather than a positional control. That is, the more the control is displaced the faster the computer image is rotated. In addition to the spring loaded rotations, the control was specified to have detents every 15 degrees on the pitch and yaw axes. This allows the control to be positioned in approximately the same position as the store so to enhance the ability of the operator to relate control movements to image movements.

The block diagram of the system specified in the final statement of work appears in Figure 2. All specified components with the exception of the attitude control and the packaging of the system were to be off the shelf equipment. On 5 May 1978 the contract was awarded to DBA Systems Inc. in Melbour FL as a competitive bid. The system was actually delivered on 5 February 1979. It has since been expanded in-house through several additional competitive bids. The current configuration of the sy appears in Figure 3.

COMPUTERS

The GAOS uses a Systems Engineering Laboratories SEL 32/75 computer system. It is a 3 computer configured with 384K bytes of core memory and hardware floating point. The system has t folloiwng peripherals:

1	Terminet-30 teleprinter (System Console)	General Electric
2	Model 9762 80 MByte disk drive	Control Oata
2	T-8640A 45ips 1600 BPI Tape Orives	Pertec Computer
1	AIM-1a Programmers Terminal	Lear Siegler
1	Model 1012 4 color drum plotter	Calcomp
1	Model 7410 Analog/Digital Subsystem	SEL
1	200 cmp Card Reader	True Oata Corp.

OPERATOR'S CONSOLE

The GADS operator's console delivered by DBA Systems Inc., includes the graphics ge or, and the video subsystem. The video system is a 1000 line system, consisting of a video monito cameras, and a video mixer. The graphics system was built by Genisco Computers Inc. and consi 1024 by 1024 raster scan system with 4 memory planes. This allows up to 16 gray levels to be d. It also includes a high speed hardware character/vector generator as well as the standard prog graphics processor. The optics system consists of two film transports projecting directly ontc ce of the video cameras. Three film transports (1-35mm and 2-16mm) are available for mounting on t transport stations. These transports may be either manually or computer controlled. Also inclu the consle is an analog/digital subsystem which interfaces the two x/y joysticks, the attitude cc , the footswitch, and the film transport controls to the computer. the actual components included are as follows:

2	16mm film transports	Vanguard Instr.
1	35 mm film transport	Vanguard Instr.
1	GCT-3000 graphics display system	Genisco Computers
1	Alphanumeric keyboard	Genisco Computer
2	7120 high res. video cameras	Cohu Electronics
1	21" high resolution B/W monitor	Conrac
1	Video mixer	OBA Systems
1	Attitude control	DBA Systems
2	x/y joysticks	Krafts Systems
1	footswitch	Line Master Switch

INFRARED CONSOLE

In late 1979, components were procured to build an infrared profile analysis console in-house. The function of this console is to process infrared profiles (recorded on video tape) using the GAOS computer system. A block diagram of the console appears in Figure 4. It operates in a manner similar to the GADS console in that it mixes video data with computer generated graphics to allow the operator to interact with the data. It is however, a NTSC compatible 525 line color system. The computer graphics generator is capable of displaying up to 256 colors from its 4096 color set simultaneously on a raster by rster basis. The graphics generator has 8 memory planes in a 480 by 512 raster configuration. It also includes a high speed hardware character/vector generator. The components included in the console are as follows.

1	GCT-300 color graphics system	Genisco Computers
1	GCT-3036 color video mixer	Genisco Computers
1	GCT-3071 alphanumeric keyboard	Genisco Computers
1	GCT-3073 3-axis joystick	Genisco Computers
1	19 inch color monitor	Mitsubishi
1	V02800 video cassette recorder	Sony
1	EFS-1A video disc recorder	Echo Science
1	PSG-311 color sync generator	Lenco Inc
1	PCO-363 NTSC chroma decorder	Lenco Inc
1	CCE-850 NTSC chrome encoder	Lenco Inc.
1	Video switching logic	In-house

SOFTWARE

All applications software running on the GADS was written at AD/KR. The software is written almost entirely in Fortran IV and runs under SEL's RTM operating system, Version 6.D. The software consists of three primary programs and several smaller programs.

MOOEL DEFINITION PRDGRAM

The Model Definition Program (MDP) is an interactive program for defining geometric models to be used for reducing data on the GADS. The program is general purpose and not restricted to defining stores. the program is written completely in ANSI Fortran IV with all system dependent code isolated to seven subroutines, making the program very easy to transport to other systems. The original version of the program was written and debugged on the CDC-6600 prior to delivery of the GADS.

MDP has a very flexable command set. Commands have been chosen to be as meaningful as possible. All input goes through a parsing subroutine which allows the user to abbreviate commands to any unique correctly spelled sequence. Additionally all parameters are input in free form with optional decimal points. Parameters may either be entered one per line, all on one line, or anything between. If the parser runs out of parameters, the user will be prompted for the next required one. This makes it easy for someone to learn the commands while not slowing down the experienced user with a long questioning and answer session. Additionally, limit checking is performed on all numbers and appropriate error messages are printed for illegal entries. The following is a brief summary of the available commands:

CENTER	Define XYZ center of an item
COPY	Copy definition of an item to another item
DELETE	Delete some attribute of an item
DISPLAY	Graphically display the object
DUPLICATE	Define item as a duplicate of another
EDGE	Define an edge
FOCAL	Define the viewing focal length
ITEM	Set current item number
LIST	List some attributres of the object
NUMBER	Re-number item to compress deleted attributes
ORIENT	Change orientation of an item
PLANE	Define a plane
PRINT	Print a listing of all attributes
QUIT	Exit the program
RADIUS	Define radii
ROTATE	Rotate the displayed image
SAVE	Save the model data base
SCALE	Scale an item
TYPE	Define an item's type
VERTEX	Define the vertex
WINDOW	Define the viewing scale
?	List all commands
<	Abort this command

When using MDP the user must decompose the object into sub-components which are refered to as items. Items may be either of two types, geometric or cylindrical. Geometric solids are items which are composed of corners and straight line segments. To define a geometric item the user first specifies X, Y, and Z locations of the verticies. One can then specify edges as existing between any two verticies. Finally, one may optionally define planes to assist in hidden line removal in future program versions. Alternately, the user can define an item as being a cylindrical solid. Essentially this type of item consists of a cylinder whose axis is along the X-axis. The user may specify the radius of the item at any two or more points along the X-axis. This allows objects like a store's body to be defined as a single item by changing sufficient radii to duplicate the taper of the body. The coordinate system used for the item definitions is shown in Figure 5. Once an item has been defined its orientation may be changed with respect to the object center. This is done by using the center command to offset it in X, Y, and/or Z or by using the orient command to change its roll, pitch, and/or yaw. Additionally, there are copy and duplicate commands, which when combined with CENTER and ORIENT, allow body features such as four identical fins to be specified very quickly.

MDP provides full editing capability for models. It allows the user to insert items, verticies, edged, planes, and radii at will. It also can list or delete any of these. The entire model data base may also be saved or retrieved from disk. Additionally, MDP allows the user to graphically display an image of any or all items on the operator's console (Tektronix 4014 terminal for CDC version). The user has the option of setting the orientation (roll, pitch, yaw) and viewing parameters (focal length, scale) prior to displaying the object. The ability to actually see the object is very useful in determining the correctness of the model since minor errors caused by typographical errors often stand out very clearly when viewed from certain orientations.

The number of items, verticies, edges, etc., in the data base are essentially limited only by the amount of memory available. The program is currently configured to allow up to 50 items. All verticies, edges, planes, and radii are contained in one array with each (except planes) requiring one element per entry. The maximum number of entries is set to 1000 at present.

ATTITUDE DETERMINATION PROGRAM

The Attitude Determination Program (ADP) is the primary data collection program for the Graphic Attitude Determining System. ADP consists of a main segment and seven overlays. The overlays and their functions are as follows:

ADPM	Main segment
ADPPR	Pre-processing of data base
ADPPA	Beginning of pass processing/calibrations
ADPDISP	Interactive display of model
ADPCMD	Keyboard command processing
ADPLOG	Logging data samples/film advance
ADPEOP	End of pass processing/data storage
ADPEXIT	End of job processing

The main segment is always core resident and controls which overlays are loaded into memory and executed. The first overlay executed is always the pre-processor (ADPPRE). This overlay begins by identifying the current version and requesting operator and mission identification information. The next step is to ask for the model identification, open the file, and read in the model data base. ADPPRE then performs some pre-processing on the model. This includes performing orientation and centering changes to geometric objects and sorting of radii by X-axis distance.

Overlay ADPPAS's are then loaded and executed. This overlay begins by asking for the pass number. If a zero is entered, then control will be passed to overlay AOPEXIT for program termination. Otherwise the data storage file will be searched for the corresponding pass number. If found, the data will be loaded into the random access temporary file. The program also checks whether there is already some data in the temporary file as a result of an abnormal termination. If so it gives the operator the option of recovering this data. If this is a new pass the program will ask for the number of calibration lines. If less than eight then there are insufficient lines to calibrate the system. In this case the program will request the X center, Y center, focal length, and window size which the operator must supply from another source. If calibrations are available the operator will be prompted for the image size in inches which has been previously read on the Telereader. A crosshair is then displayed which the operator positions on the sides of the calibration cube shown in Figure 6. Once these measurements have been made, the computer uses the data to solve for the optical center of the camera in terms of display screen coordinates, the magnification of the GAOS optical system in screen coordinates, and the focal length of the camera. AOPPA then initializes several other variables and returns to the main segment.

Control is now passed to overlay AOPOISP. This overlay then begins by determining whether or not the program is in the edit mode. If so, the program reads the previously measured attitude data from the temporary data file and positions the model appropriately. If not in edit mode the program will locate the requested number of fixed frame points. These points may be used in a later data reduction program to remove the effects of wing flexure from the data. Alternately, a separate model of the aircraft wing could be matched to precisely determine the location of the camera in each frame. The program then begins a loop where it clears all points in a Genisco memory plane; draws the geometric solids; draws the cylindrical solids; writes the attitude parameters; enables display of the memory plane just written into; enables writing of the other plane; updates the A/D readings of the controls; checks for and processes function keys; and then repeats the cycle. It will remain in this loop until a key, a function button, or the footswitch is pressed. Pressing a key will cause control to pass to overlay ADPCMO. Pressing a function button will cause either a change in the state of various display functions, or will cause control to pass to overlays AOPEOP or AOPEXIT. Pressing the footswitch will cause control to pass to overlay AOPLOG to log the data from the current frame.

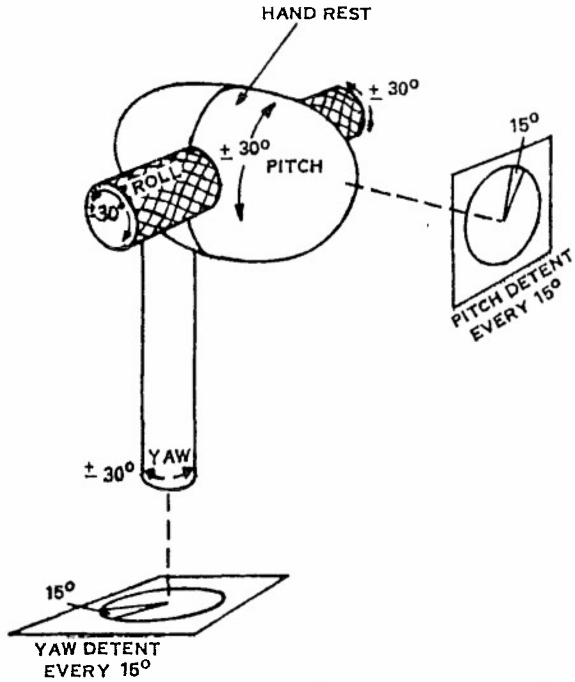
Upon starting overlay AOPLOG, all attitude information is saved in a buffet which is then written to the random access temporary data file. The program then advances the proper film transport. If the auto predict mode is enabled, the computer will then predict the next image location based on the last two points and the error for the previous prediction and set the initial coordinates of the display for the next frame. Control is then passed back to overlay AOPOISP.

When the end of pass function button is pressed, overlay ADPEOP is invoked. This overlay scans through the existing data file to locate the current pass. If it already exists, the program replaces it with the new data. Otherwise, it will insert the new pass into the data file. This file is sequential by pass number. Control is then passed to overlay AOPPASS to initialize a new pass.

Overlay AOPEXIT is invoked for job termination. It makes an entry containing the number of frames read and the elapsed time in the accounting file, produces an optional raw data dump, and then restarts or terminates the program.

BOMB SYSTEM OUTPUT PROGRAM

The Bomb System Output Program (BSOP) is currently the primary data reduction program running on the GADS. The program, written by M.A. Smith, inputs data from the Attitude Determination Program, translates the data to the center of gravity of the store, and then references all data to its pre-release position. The program also changes the coordinate system from the one shown in Figure 5 as used by ADP to the one shown in Figure 7. In this coordinate system Y, roll, and yaw are all defined to be positive for outboard motions. Thus their signs depend on which side of the aircraft the store is suspended. These conventions are based on current projects and can be easily changed for others. After translation the data can optionally be smoothed by fitting the data to either a qubic or a quadratic equation. Smoothing is selectable over 3 to 99 data points. BSOP produces two types of output, listings and plots. The listings currently available show raw position data, smoothed position data, and/or velocity data for the six degrees of freedom on a frame by frame basis. Currently available plots show the six degrees of freedom as either smoothed or raw positional data versus time and pitch, yaw, and/or Y distances versus Z distances. Figure 8 shows a sample plot.



ATTITUDE CONTROL DEVICE
— FUNCTIONAL DRAWING —

Figure 1

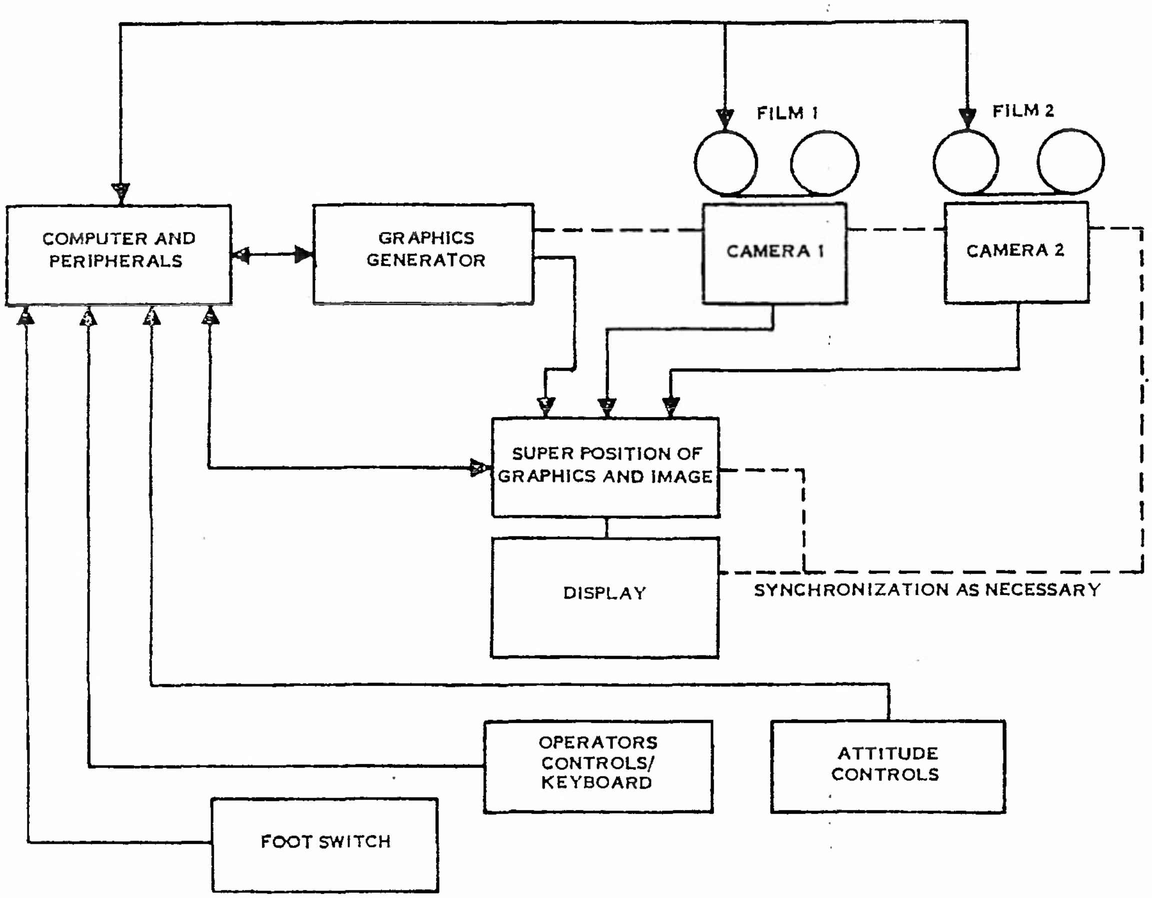


Figure 2 - Functional Block Diagram

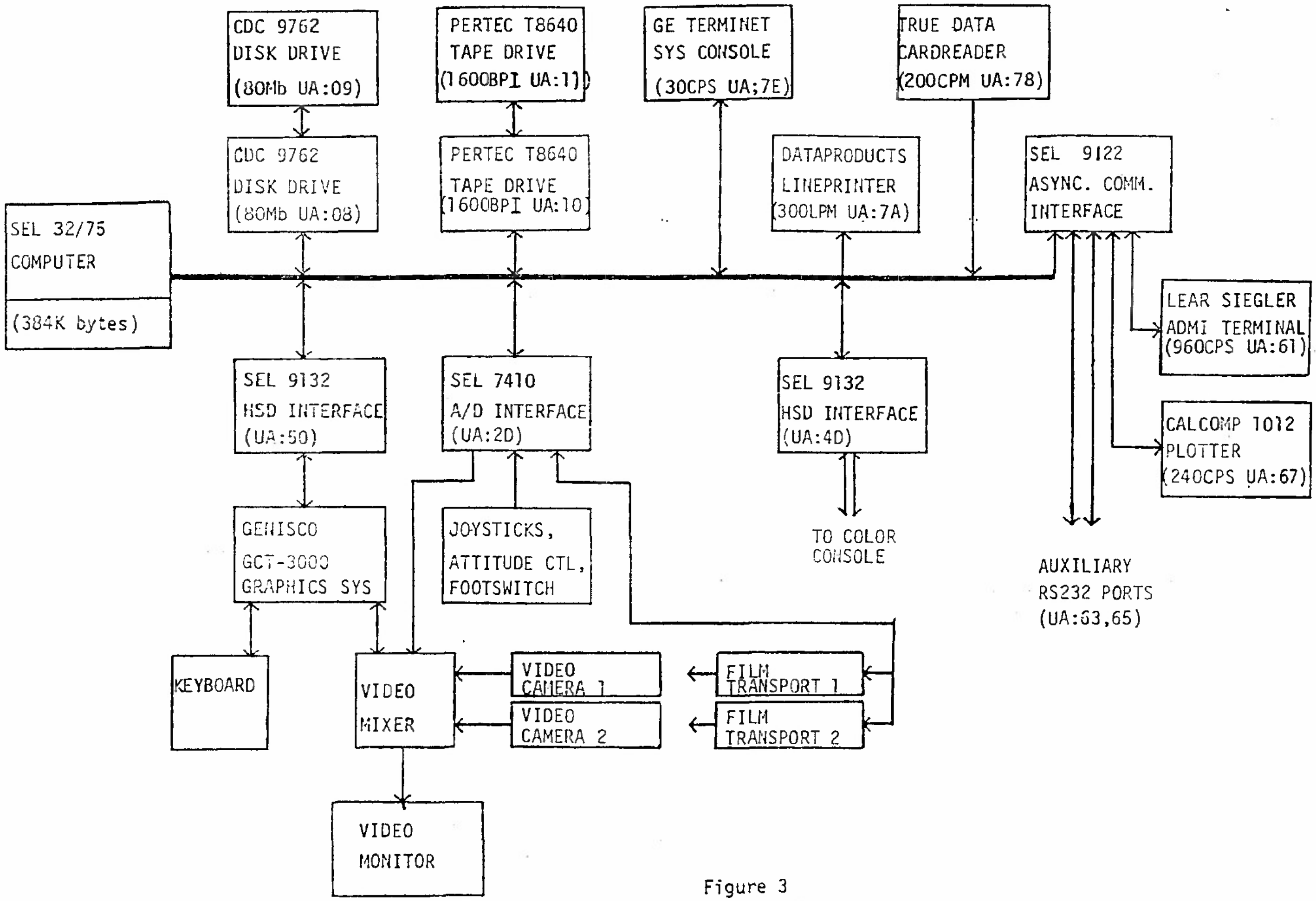


Figure 3
Graphic Attitude Determining System Block Diagram

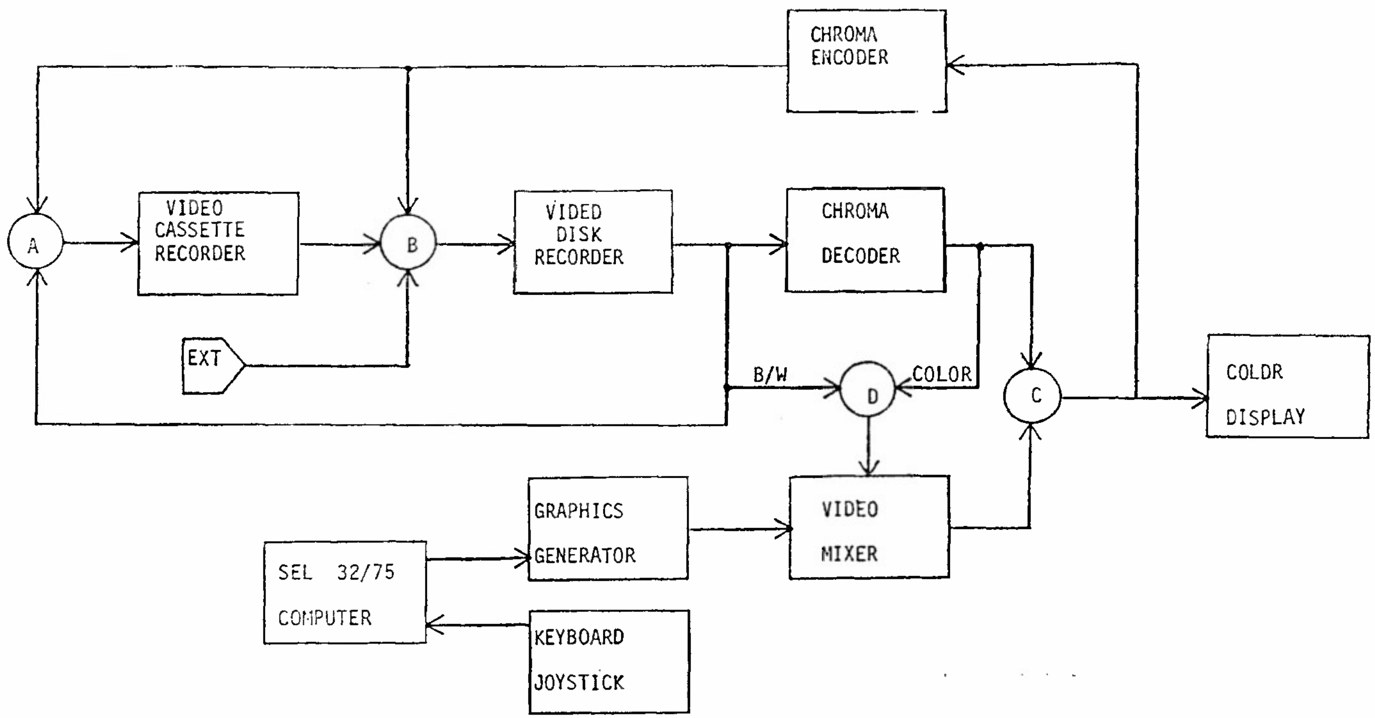


Figure 4 - Infrared Profile Analysis Console

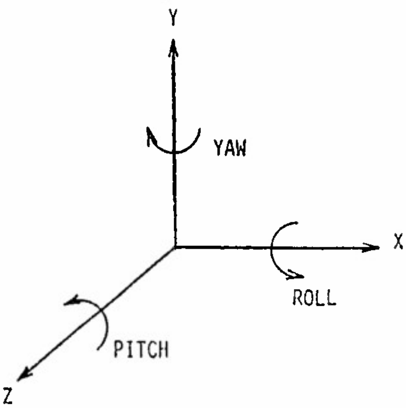


Figure 5 - MDP Coordinate System

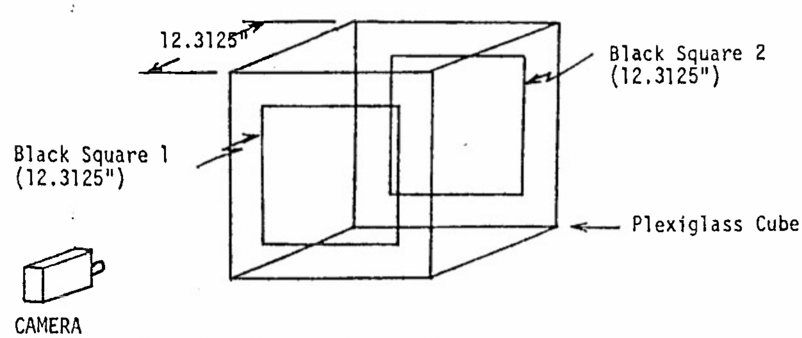


Figure 6 - Calibration Setup

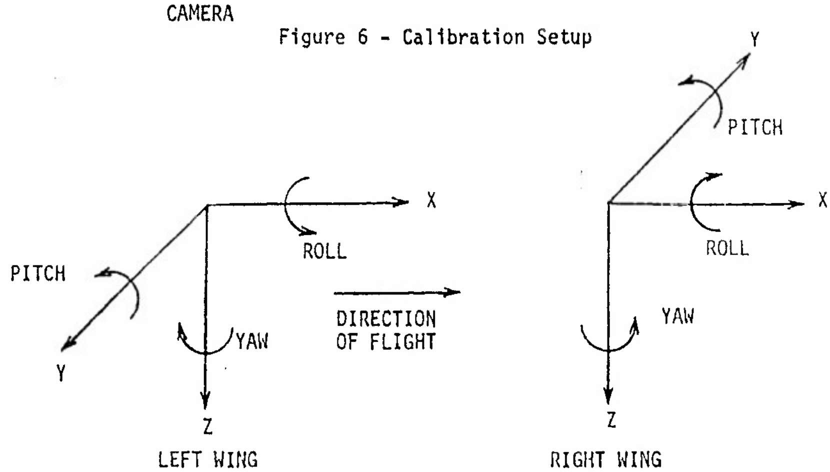
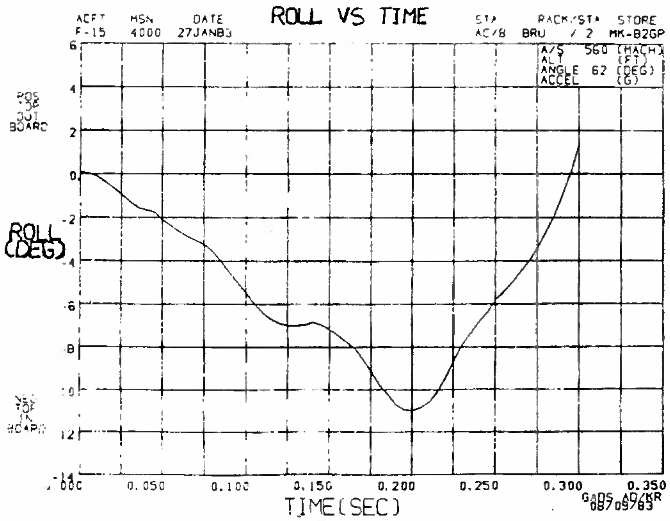


Figure 7 - BSOP Coordinate System



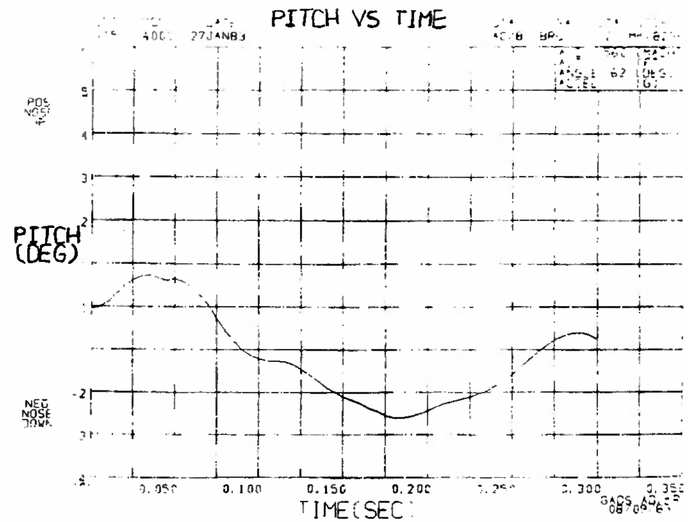


Figure 8 (1 of 4)

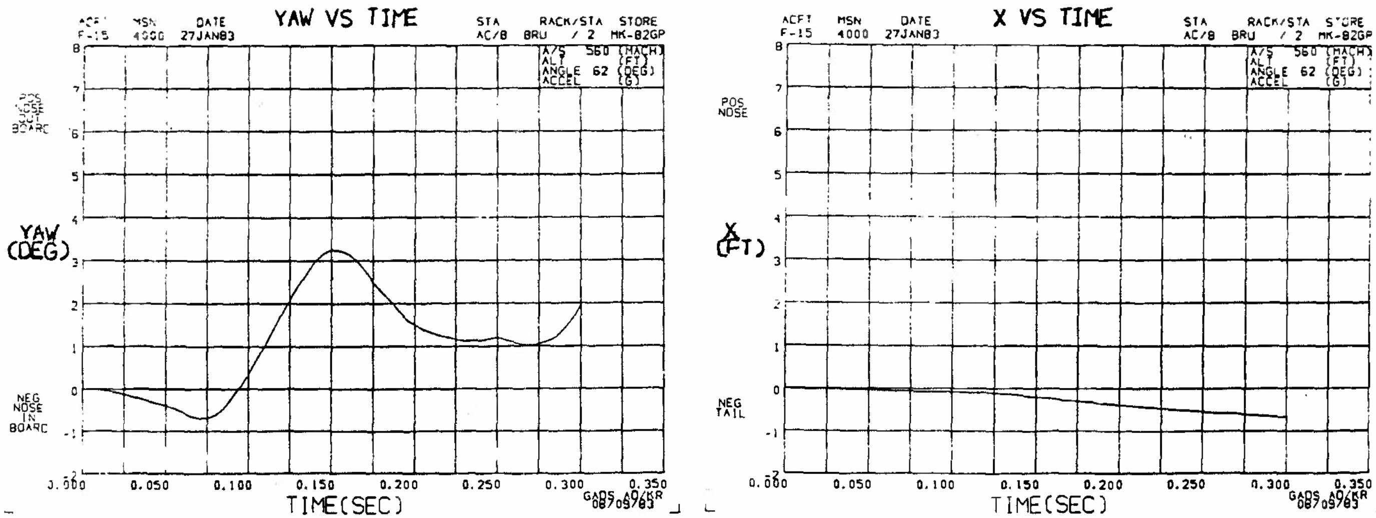
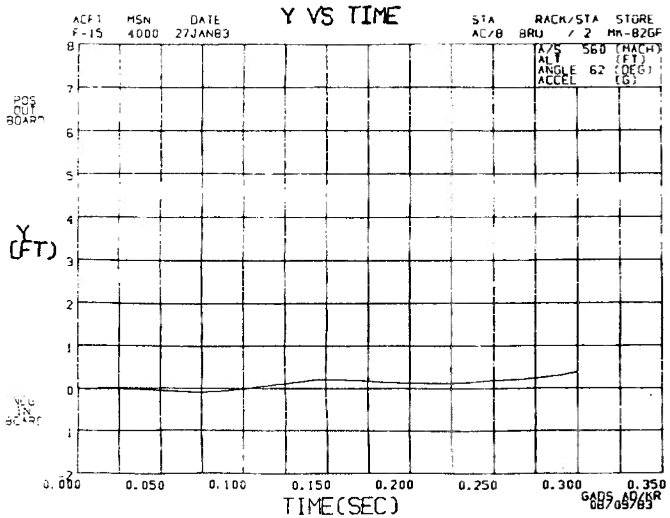


Figure 8 (2 of 4)



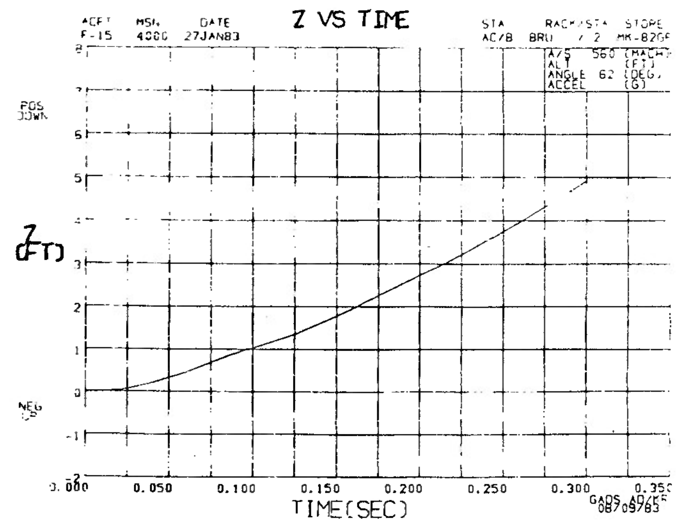
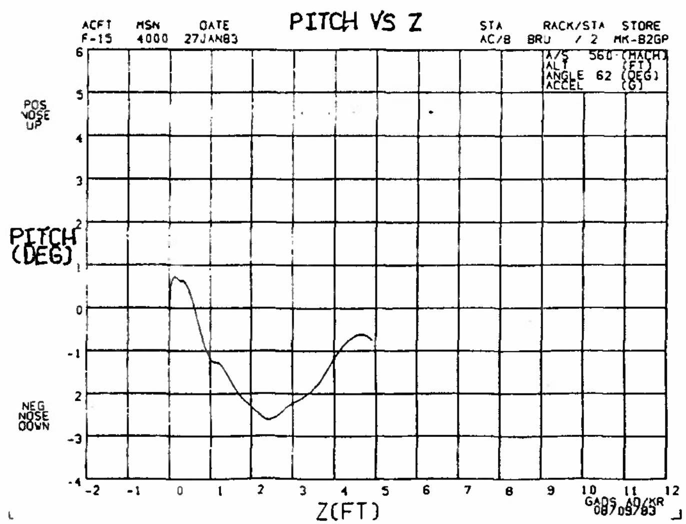


Figure 8 (3 of 4)



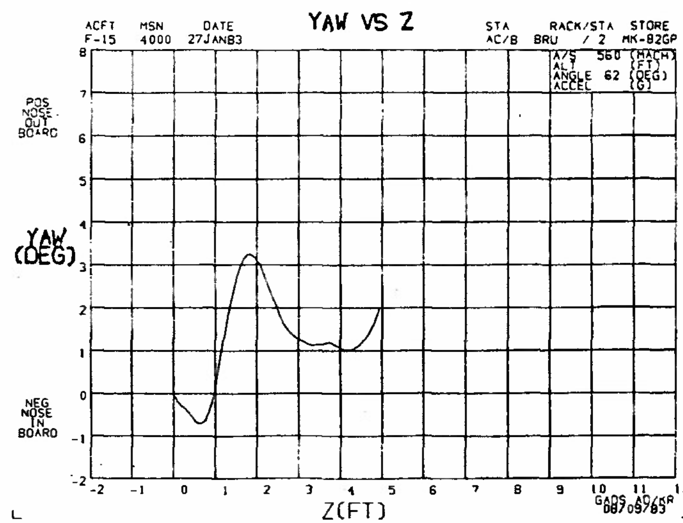


Figure 8 (4 of 4)

APPENDIX D

PRECISION MEASUREMENT FACILITY

OFFICE FOR AIRCRAFT COMPATIBILITY

3246 TEST WING/TY

Eglin Air Force Base, FL 32542

APRIL 1984

NOTE: For the sake of brivity, only typical, representative, plots are included herein.

THE PRECISION MEASUREMENT FACILITY (PMF)

The Precision Measurement Facility at located at building 990 on Eglin AFB. The outward appearance of this facility and its surrounding area is that of an isolated shop with little significance. However, after a closer look, one will discover quite the contrary. Upon entering, first thing to catch the eye is the 861/B Airdyne Mass Properties Measuring Unit ("Big-I"). This is an impressive piece of equipment and is essential for the PMF to fulfill its mission.

The mission of the personnel assigned to the PMF is to determine and provide the accurate weight, Center of Gravity (CG), and the moments of inertia for stores as required. The mission is a short one, but the accomplishment of it requires a great deal of technical knowledge and hands-on experience. The equipment used to determine this information is complex and sensitive. The information provided by the "BIG-I" is vital. Prior to its operation in 1967, there were problems encountered during some flutter tests. After a post-flight investigation, it was determined these problems occurred as a result of incorrect information concerning the CG and moment of inertia of stores. The operation of this facility provides the project officer with a source for determining whether or not the stores meet the specified tolerances prior to flight. It is impossible to estimate the number of problems and costs created by out of tolerance stores which could have been avoided. However, it is safe to assume the "BIG-I" has saved the Air Force a good deal of money since it's inception.

There are six essential items required in order to determine a store's weight, CG and moment of inertia. These items are the "Big-I", surveyor's transit, hoist, torque wrench, calculator, and a small ruler. Before the operating procedures are explained there are a few things one should know about the "Big-I".

The "Big-I" consists of 3 parts. The first of these is the measurement table. The measurement table is where the store is actually placed. It is accompanied by two separate adapters. The primary adapter is a modified MJ-3 bomb rack. This adapter was designed so the table could handle stores of a cylindrical shape. The second adapter is used to accomodate narrow flat surfaced stores. The second major part is the control console. This item is equipped with the 532A Hewlett Packard counter-timer. The counter-timer is where the function settings and reading displays are located. The third and final part is the stress guage. This piece of equipment is used to weigh the store. It provides the counter-timer with the reading needed to obtain the weight. The "Big-I" operates on a dry nitrogen gas system and requires at least 125 psi. The accuracy rate of the "Big-I" is outstanding and the limitations are few (See Table I). The assurance of the accuracy rates are maintained by a weekly CG calibration and a monthly calibration of the moment of inertia.

The operating procedures are broken down into three areas: warm-up, actual work performance, and shutdown procedures.

During warm-up, the transit is sighted in with reference marks on the measurement table. There are also calculations performed using formulas 1 and 2 of Table II. It is essential to obtain these numbers to assure the "Big-I" is properly warmed-up and to perform the actual work. The time required for warm-up ranges from one to two hours. This time varies according to the outside temperature. (the colder it is the longer it takes)

The following is a step-by-step explanation of how the weight, CG, and moment of inertia are actually determined. A photo sequence of the operation is provided so that it may be more clearly understood.

1. The store is first hoisted with the stress gauge. There it is suspended while the information is taken from the counter-timer to determine the store's weight (Figure 1). The weight is determined by using formula 3 listed in Table II.

2. The stress gauge is then replaced by a bomb sling to prevent it from being damaged. The store is then transported along the hoist rail and positioned on the measurement table. (Figure 2)

3. The store is then sighted in and a reference point is marked on it. This is done by using a small ruler and the transit (Figure 3). As this is being done the counter-timer is being set to acquire the necessary readings for determining the CG (Figure 4).

4. Next, the measurement table is supplied with 100 psi of gas pressure an the table is lowered onto the gas bearings (Figure 5).

5. The table is then rotated to 90 degrees and 270 degrees (Figure 6). The readings are taken from each of these locations and calculated using formula 4 of Table II (Figures 7 and 8). The result is relayed to personnel at the measurement table.

6. Using the ruler and the reference point marked in step 3, the CG is marked. Whether the result is a positive or negative number will determine whether the CG is forward or aft of the reference point (Figure 9). During this step, the settings on the counter-timer are once again changed to obtain the required readings for the moments of inertia.

7. At this time the table is positioned at zero degrees and torqued to 400 inch-pounds. The item is then oscillated at 4 degrees. While the store is oscillating, three readings are obtained to determine it's yaw. This is done from calculations using formulas 5 and 6 of Table II.

8. The store is then rotated on the table to a 90 degree angle and once again oscillated at 4 degrees. Three new readings are taken and again calculated using formulas 5 and 6. The results of this will determine the store's pitch.

9. The table is then untorqued and returned to 315 degrees (which is in line with the

transit). Then the table is raised from the gas bearings and the gas pressure is cut off.

10. The store is then removed from the table and returned to the trailer. There it is stenciled with the information and tied down (Figures 10 and 11).

After all required stores have been completed the "Big-I" is shut down.

Table I

1. Accuracy:

   a. Weight = $\pm$ 0.2%

   b. Center of Gravity - $\pm$ 0.005"

   c. Moments of Inertia - $\pm$ 0.5%

2. Limitations:

   a. Store length must range from 2' to 20'

   b. Store weight must range from 50 to 4000 pounds.

   c. Store shape - sometimes shape or special construction make it impossible to position on the table. Because of the "Big-I's" versitality, this is an uncommon occurance, and can only be determined by actually trying to work with the store.

Table II

1. Terms Used:

   a. Constant = K: This is a number derived during the warm-up. It is used to calculate weights and to ensure the "Big-I" is properly warmed-up. When K = 98846 to 99270 the "Big-I" is ready for use.

   b. MT: This is the term used to refer to the empty weight of the stress gauge.

   c. T_1^2: This is the result of a calculation performed from oscillating the table without a store on it. It is used when calculating moments of inertia.

2. Mathematical Formulas Used:

   a. Formula #1. WT mass - MT = Memory (M+), 231.3 $\div$ Memory Recall MR = K

   b. Formula #2. Total of 3 Readings $\div$ 3000, Squared (X=) = T_1^2

   c. Formula #3. Store Weight - MT x K = Store's True Weight

   d. Formula #4. 90° - 270° x 15900 $\div$ Store's True WT $\div$ 36.16 = ______ x Memory recall = _____

   e. Formula #5. CG $\div$ 12 ________ (x=) Memory +, store's true WT $\div$ 36.16 = ______ x Memory recall = ________ (result is held in memory and recalled in Forumla #6)

   f. Formula #6. Total of 3 readings $\div$ 3000 = _____ (x=) - T_1^2 = ____ x 7.50 = _______ - Memory recall = moments of inertia.

NOTE: The above formulas were derived by the Miller Research Corporation.

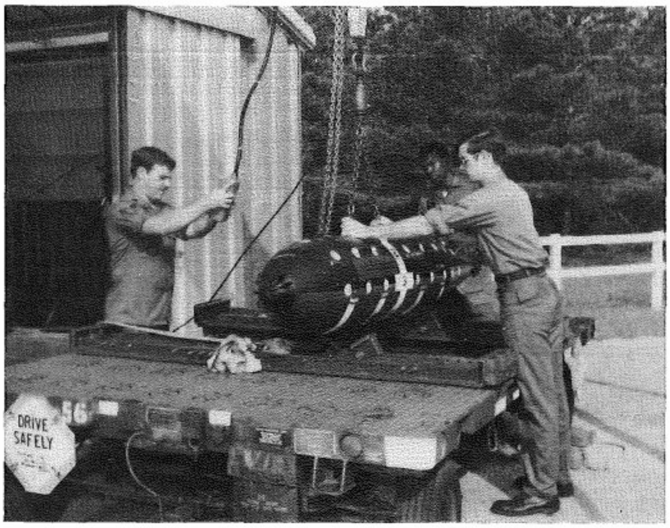


Figure 1

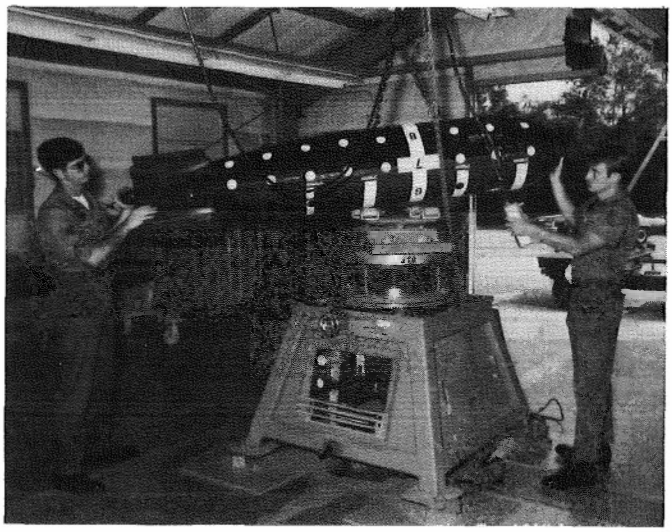


Figure 2

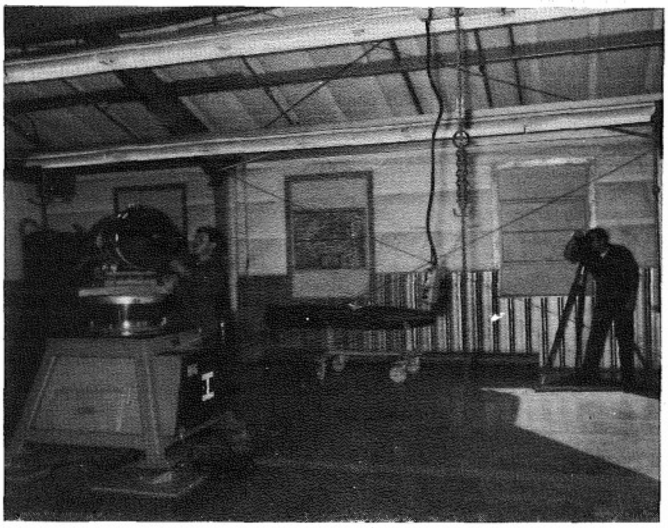


Figure 3

Figure 4

Figure 5

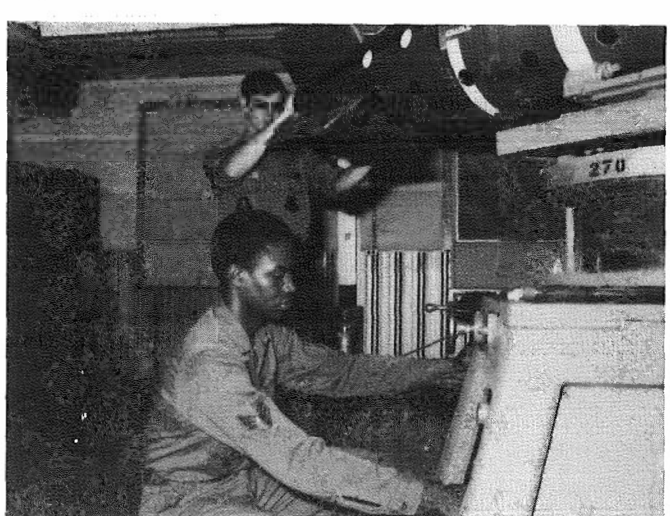


Figure 6

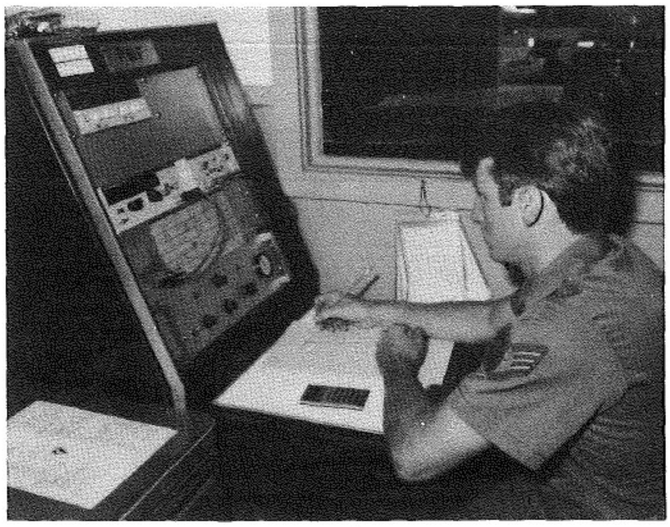


Figure 7

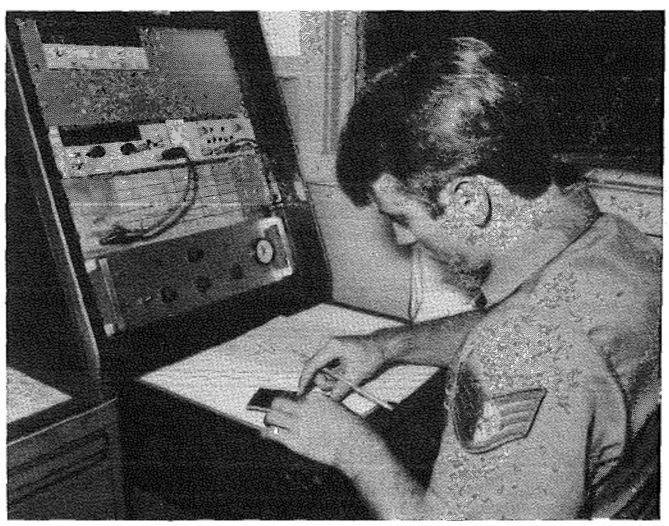


Figure 8

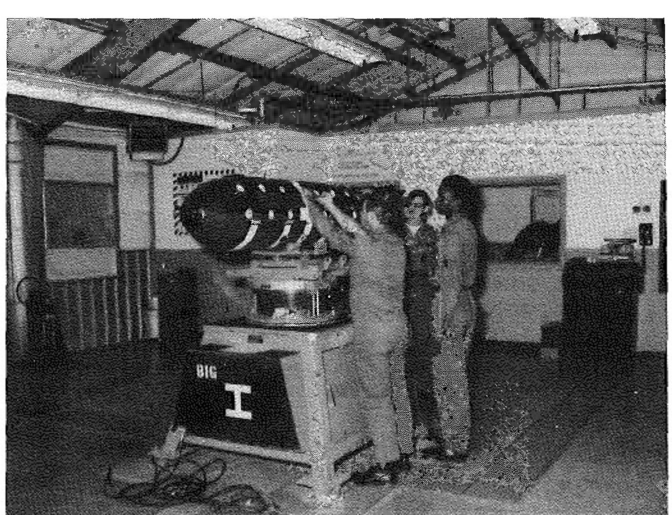


Figure 9

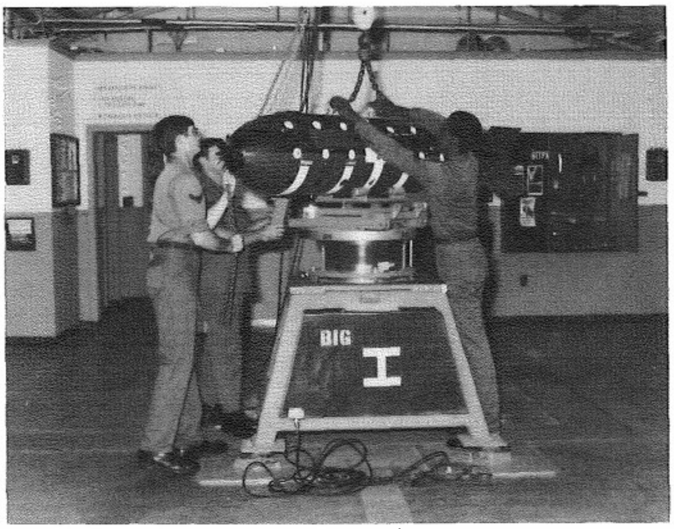


Figure 10

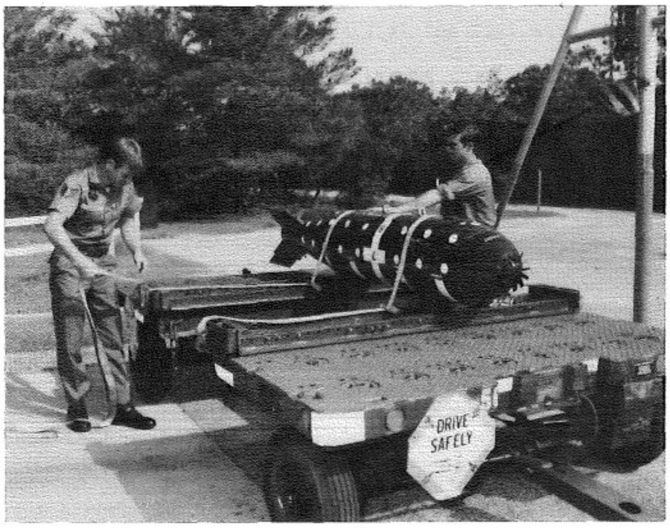


Figure 11

APPENDIX E

USAF STORE DELIVERY ANALYSIS METHODOLOGY

OFFICE FOR AIRCRAFT COMPATIBILITY

3246 TEST WING/TY

Eglin Air Force Base, FL 32542

APRIL 1984

NOTE: For the sake of brivity, only typical, representative, plots are included herein.

USAF STORE DELIVERY ANALYSIS METHODOLOGY

INTRODUCTION

In order to aim a store so that it will hit the target, it is necessary to know the flight characteristics of the store as it travels the required distance to the target. This appendix discusses exterior ballistics of unguided stores released from fighter as well as bomber aircraft. This discussion covers the USAF method of test considerations, data collection, data reduction, and data analysis.

TEST CONSIDERATIONS:

Flight characteristics of a store are obtained by conducting controlled tests. Factors to be considered when designing the test are the store release envelopes, the types of data to be collected, and the necessary number of stores to be released. The release envelope is usually determined when the store is developed; however, this may be outside of the operational envelope of the using community. The number of stores required to gather the necessary flight characteristics data will depend upon the type of store tested. Basically, there are two types of stores. The first is a store that has a cylindrical shape, usually with stabilizing fins, that remains intact until it impacts the targeted area. The second type is a container, that may have stabilizing fins, designed to function at a predetermined time after release or at a designated altitude to dispense submunitions. Either type may have other events that alter the store trajectory. The functioning type store will require more testing because the submunitions form a pattern that must be determined. The type of data required is the same for all stores except for impact pattern data and such modifications as chutes or other retardation devices.

COLLECTING TEST DATA:

The aircraft and store are tracked by, a minimum of three, cinetheodolite cameras operating at 30 frames per second with Integrated Range Instrumentation Group (IRIG) time to record azimuth and elevation data. The aircraft is tracked from five seconds prior to release to two seconds after release. The store is tracked from release to impact for intact types, and from release to functioning for functioning types. Submunitions are usually too small to track. In addition to cinetheodolites, the aircraft and store are tracked with a medium speed tracking camera operating at 90 frames per second with IRIG time to record the time of store release as well as other event times. Other methods of obtaining release time have been used but were not found to be accurate. Since submunitions are too small to track with cinetheodolite and medium speed tracking cameras, Milliken or other type fixed cameras with IRIG time are positioned along a grid impact area to obtain impact time, velocity, and angle data. The fixed cameras are used only if the functioning type store contains a few submunitions (approximately 30 or less). The reason being that the camera readings must be correlated with the submunition impact points. The grid impact area is used to obtain polar coordinates of the individual submunition impacts. The dud count for High Explosive (HE) submunitions are obtained during impact scoring. The weight of each store is obtained and correlated with the aircraft/rack station for each drop. Meteorological data is obtained on each misison. The atmospheric properties (temperature and density) are obtained from daily standard base upper air observations. The wind direction and velocity data are obtained by tracking a Pilot Balloon (PIBAL) at the test site with the cinetheodolites.

REDUCTION OF TEST DATA:

The cameras and associated film records provide azimuth and elevation data and film images at precise time intervals with an accuracy of approximately .005 degrees. The exact position of each cinetheodolite site is determined by first order geodetic survey, and the cameras are located and properly oriented in a topocentric rectangular coordinate system. Precise camera orientation is accomplished and checked by on-site leveling procedures and calculations utilizing fixed boresight targets. Multiple station solutions for individual space position points are obtained. Spacial position accuracy to one foot has been realized; and, depending upon geometry, accuracy of better than five feet is usually accomplished using three to six cameras.

The time to start the reduction is determined and associated with the frames to be read. These readings are recorded on magnetic tapes containing mission identifying information, frame numbers used for time correlation, aziumth, elevation, and X and Y tracking error from the center of the frame to the point tracked (normally the nose of the aircraft). These tapes, as well as information pertaining to the mission, are inputs to a data reduction program.

The data reduction program first corrects the azimuth and elevation angles from each camera for tracking and boresight errors, such as horizontal and vertical collimation and zero set to give azimuth measured from true North. Next the coordinates of each camera site with respect to the origin are computed as well as the rotation matrices necessary to reference the measurements to a common plane containing the origin.

The data from the first two cameras with readings for a point are rotated to a common plane and a two-station Bodwell solution is performed to obtain an estimate of the position. The Bodwell solution minimizes the square of the distance between the two lines of sight to arrive at the best result. This preliminary position estimate is used to compute a refraction correction for each camera with readings for this point.

The direction cosines from the refraction corrected angles are rotated to the common plane, and another two-station Bodwell solution is determined which gives the initial values for a Davis solution, an iterative procedure which minimuzes the sum of the squares of the angular residual; i.e., the difference between the corrected input observations and the true angles to the computed point.

After the Davis solution has converged for a particular point, the angular residuals are examined in order to eliminate stations or cameras with bad readings. The final solution either has all residuals less than 0.02 degrees or is the best possible result from the input.

The convariance matrix from the final iteration and the unit variance (sum square residuals divided by the degrees of freedom) are combined to give the error in position for the point.

$$\text{Error} = (\sigma_x^2 + \sigma_y^2 + \sigma_z^2)^{1/2}$$

As the data are read into the editing segment of the program, the position error is compared to a standard value so that samples can be eliminated which have an error larger that the standard. This standard is the mean plus three sigma value of the position error for all points in the pass for which a reasonable solution was found. Additional editing is performed by fitting a moving arc polynomial of second or third degree to the coordinates and correcting values which fall too far off the curve.

The final step is to fit the moving arc polynomial to the corrected coordinates to obtain smoothed position. The first and second derivatives or the polynomials give velocity and acceleration, and various other parameters are computed from these.

The smoothed aircraft Time-Space-Position-Information (TSPI) is normally printed at 0.2 second intervals and contain such parameters as position, velocity, acceleration, Mach number, dynamic pressure and flight path angle correlated with time. Release time (T-0) being the time of first movement of the store from the aircraft is determined from reading the medium speed tracking camera film.

The store TSPI data are obtained using the same reduction method as for the aircraft. The store event times are obtained from reading the time-correlated medium speed tracking film. These event times include such things as fin opening, chute deployment, chute separation, fins canting, and time of impact. For functioning type stores, the time of impact is obtained from reading the fixed camera film. The submunition impact velocity and angle data are computed by correlating the surveyed impact point with the fixed camera readings. Due to the correlation of the surveyed impact with the film readings, impact velocity and angle data cannot be obtained on most of the functioning type stores because of the number of submunitions.

Individual submunition impact points are surveyed in polar coordinates. These polar coordinates are transformed to the same rectangualr coordinates as the aircraft and store.

The PIBAL tracked cinetheodolite film data are reduced using the same method as that for the aircraft and store. The position and velocity data are then translated to wind direction and velocity. The temperature and density data are obtained from the atmospheric observation nearest the time of the mission.

ANALYSIS OF TEST DATA:

An unguided store ballistic analysis is the development of the store ballistic data (drag coefficient, event times, etc) for use in a mathematical model to predict the flight path of the store from release to impact. The analysis also develops the methodology and necessary data to predict the impact pattern for functioning type weapons.

In order to analyze the ballistic performance of the store, theoretical trajectories are computed using an in-house "Unguided Store Ballistic Analysis Program", with the following information.

1. Positions and velocities of the store at release (T-0) as determined from the TSPI data for the aircraft. The positions are corrected to the position of the store on the aircraft (since the cinetheodolite film measurements are made on the nose of the aircraft).

2. Velocity at which the store is ejected from the aircraft (ejection velocity).

3. Store diameter and observed weight.

4. Drag coefficient (K_D vs Mach number or time).

5. Meteorological data (temperature, density, wind direction and velocity).

6. Observed event times that affect the drag of the store.

7. The "Particle" equations of motion.

The "particle" equations of motion assume that the only forces acting on a store are (a) the drag force which acts in a direction opposite to that of the air velocity vector of the store, and (b) gravity.

The drag force, D, is then:

$D = ma = \rho K_D d^2 V^2$ where

D = drag force (lb - ft/sec^2)

m = mass of store (lb)

a = acceleration of store due to drag (ft/sec^2)

p = air density (lb/ft^3)

k = drag coefficient (dimensionless)

d = store diameter (ft)

v = air velocity of store (ft/sec)

C_D, used by many aerodynamicists, is related to K_D by the formula

$$K_D = \frac{\pi}{8} C_D$$

and drag, D, may be expressed as

$$D = \frac{1}{2} \rho C_D S v^2$$

where $S = \frac{\pi d^2}{4}$ = cross secitonal area.

The "Unguided Store Ballistic Analysis Computer Program" conputes point mass three-dimensional trajectories using the modified Euler integration method.

Using the above program inputs, theoretical trajectories are computed and compared with the observed trajectories (TSPI). This comparison is usually at 1.0 second intervals as well as at impact or trajectory termination. If the delta range and time (observed minus computed) deviations for each store are large and biased in one direction, it must be determined if the deviations are due to drag or separation effects. Separation effects are due to the interaction between the weapon and the airflow about the aircraft. In order to make the distinction between drag and separation effects, additional trajectories are computed using the positions and velocities at some time T-1 after release. Time T-1 is usually 1.0 second but should be far enough along the observed store trajecatory for the store to settle down. If the comparison of the T-1 trajectories with the observed produce large and biased deviations, the initial drag must be adjusted or derived.

After adjusting or deriving the drag, trajectories starting at time T-0 with the new drag are computed. If the comparison of these trajectories with the observed produce large deviations, a separation effect analysis must be accomplished. If the deviations are small this portion of the analysis is complete.

If the comparison of the T-1 trajectories with the observed produce small deviations, the initial drag is applicable. The large deviations obtained when comparing the T-0 trajectories with the observed are due to separation effects. Therefore, a separation effect analysis must be performed.

As mentioned earlier, the separation effects are due to the interaction between the store and the aircraft flowfield. When a store is released from the aircraft, it is immersed in the common flowfield and its motion is temporarily dominated by the flowfield interaction. The interacting flow is not uniform around the store as it would be in free flight in an unperturbed atmosphere, and the store's trajectory may be significantly perturbed.

The store is in the aircraft flowfield for only a short time (less than a second) before entering freestreem conditions. When the store moves away from the flowfield interaction region, it is usually oscillating in pitch and yaw as well as changing its roll rate. As the store continues along its trajectory, it motion damps to trimmed conditions. When the store's motion achieves quasi-steady conditions, it falls along a point mass trajectory to impact or to its functioning point.

Several methods of analyzing the motion of the store due to aircraft flowfields have been studied. The most accurate method would be to use a 6-degree-of-freedom (6-DOF) dynamic simulation. A 6-DOF simulation would require a large data base and is not cost effective when generating ballistic tables for the Aircrew Store Delivery Manual (-25 and -34 series T.O.).

The method currently used is a second order polynomial or least squares fit of the horizontal and vertical velocity differences at time T-1 with T-0 Mach number and dynamic pressure respectively. An attempt is made to have one curve for a given store from all delivery aircraft.

After the store drag has been verified or derived, theoretical trajectories starting at time T-D are computed to obtain the difference in the observed and computed horizontal and vertical velocity components at time T-1, time T-1 being the trajectory start time when verifying or deriving the store drag. The velocity differences are then rotated to horizontal through the store release angle obtained at time T-0. A curve or straight line is then fited to the rotated horizontal velocity differences and Mach number. A curve or straight line is also fited to the rotated vertical velocity differences and dynamic pressure. The coefficients of the curve or line fit are then used in an algorithm to compute the release adjustment to be applied to the store's velocity components at time T-0. This adjustment will force the theoretical store trajectory to have the approximate position and velocity as the observed at time T-1. This method works well within the range of test data and is cost effective when producing aircrew store delivery manuals. Therefore, it is important, when designing the test, to cover the operational range of the store from all aircraft.

The analysis of the test data to predict the flight path of intact and functioning types stores is complete. For functioning type stores, the observed impact patterns must be analyzed to determine the patern prediction methodology and/or data.

To analyze the patterns, the first thing is to determine their shape (circle, ellipses, etc.)

and dimensions (diameter, major and minor axis, etc.). The USAF has looked at statistical methods of determining pattern shapes and dimensions. In almost all patterns there are outlying submunitions. Outlying submunitions are those that, for some reason, do not follow their designed flight path. The outlying submunitions that are greater than three sigma from the Mean Point of Impact (MPI) are rejected. After rejecting the outliers, the circles that contain eighty and ninety percent of the submunitions are calculated. The centers of the circles and ellipses are the MPI. This method works well if you have a uniformly distributed pattern. If the pattern has a heavy population of submunitions in the front or back, right or left side, the MPI is biased toward this area. Using the bias MPI to calculate the circles and ellipses will result in an area within the circles and ellipes that does not contain submunitions. Most patterns are not uniformly distributed; therefore, this method is not used.

The method used is to first eliminate the outlying submunitions by visually inspecting the plots of the impact patterns. An attempt is made to have ninety percent or more of the submunitions to remain within the pattern. This pattern is defined as the effective pattern. At the time the outliers are eliminated, the geometric shape of the pattern is determined and drawn on the plot to encompass the effective pattern. The Geometric Center of Impact (GCI) being the center of the geometric shape (i.e. center of the circle, ellipse, rectangle, etc.). Now the effective pattern dimension must be determined by measuring the diameter of the circle, the major and minor axis of the ellipse or length and width of the rectangle. Now that each observed pattern has been analyzed to determine the shape and size, the pattern prediction methodology must be developed. There are several methods of predicting patterns. The two primary methods are the angular dispersion and forced ejection. The angular dispersion method of predicting patterns assumes that, as the functioning munition opens (dispenser opening) and the submunitions are exposed to ram air, the submunitions slightly separate from each other and follow their individual trajectories. This results in the submunitions departing from dispenser opening with a characteristic angular displacement about the normal dispenser velocity vector. This displacement does not provide for natural or designed dispersion of the submunitions induced during their free flight.

To derive the displacement angle(s), theoretical trajectories are computed using the dispenser opening conditions (positions and velocities), adjusted, in both the vertical and lateral planes, by the displacement angles(s) and the necessary submunition data. The theoretical pattern dimensions are then compared with the observed effective pattern dimensions. This process is repeated until a vertical and lateral displacement angle is derived so that the theoretical patterns closely approximate the observed patterns. The vertical and lateral displacement angles may or may not be the same. The angular displacements may not be used in the functioning type munition model to predict the pattern dimensions.

The forced ejection method of predicting patterns assumes that the submunitions are expelled or ejected perpendicular to the dispenser velocity vector. The tangential velocity is a function of the submunition ejection system (i.e., gas generator, explosive charge, spinning dispenser, etc.).

Theoretical trajectories are computed in the same manner as for the angular dispersion method except the velocity vector at dispenser opening is adjusted, in both the vertical and lateral planes, by the tangential velocity vector. The theoretical pattern dimensions are compared with the observed pattern dimensions, and if necessary, the process is repeated until a tangential velocity is derived so that the theoretical patterns closely approximates the observed patterns. The tangential velocity may now be used in the mathematical modeling of function type stores to predict the pattern dimensions.

Once the ballistic data to model the store flight path and to predict pattern dimensions for functioning type stores have been developed, the analysis is complete.

Annex 1

AGARD FLIGHT TEST INSTRUMENTATION AND FLIGHT TEST TECHNIQUES SERIES

1. Volumes in the AGARD Flight Test Instrumentation Series, AGARDograph 160

Volume Number	*Title*	*Publication Date*
1.	Basic Principles of Flight Test Instrumentation Engineering by A.Pool and D.Bosman	1974
2.	In-Flight Temperature Measurements by F.Trenkle and M.Reinhardt	1973
3.	The Measurement of Fuel Flow by J.T.France	1972
4.	The Measurement of Engine Rotation Speed by M.Vedrunes	1973
5.	Magnetic Recording of Flight Test Data by G.E.Bennett	1974
6.	Open and Closed Loop Accelerometers by I.Mclaren	1974
7.	Strain Gauge Measurements on Aircraft by E.Kottkamp, H.Wilhelm and D.Kohl	1976
8.	Linear and Angular Position Measurement of Aircraft Components by J.C.van der Linden and H.A.Mensink	1977
9.	Aeroelastic Flight Test Techniques and Instrumentation by J.W.G.van Nunen and G.Piazzoli	1979
10.	Helicopter Flight Test Instrumentation by K.R.Ferrell	1980
11.	Pressure and Flow Measurement by W.Wuest	1980
12.	Aircraft Flight Test Data Processing — A Review of the State of the Art by L.J.Smith and N.O.Matthews	1980
13.	Practical Aspects of Instrumentation System Installation by R.W.Borek	1981
14.	The Analysis of Random Data by D.A.Williams	1981
15.	Gyroscopic Instruments and their Application to Flight Testing by B.Stieler and H.Winter	1982
16.	Trajectory Measurements for Take-off and Landing Test and Other Short-Range Applications by P.de Benque d'Agut, H.Riebeek and A.Pool	1985
17.	Analogue Signal Conditioning for Flight Test Instrumentation by D.W.Veatch and R.K.Bogue	1986

At the time of publication of the present volume the following volume was in preparation:

Microprocessor Applications in Airborne Flight Test Instrumentation
by M.Prickett

2. Volumes in the AGARD Flight Test Techniques Series

Number	*Title*	*Publication Date*
AG 237	Guide to In-Flight Thrust Measurement of Turbojets and Fan Engines by the MIDAP Study Group (UK)	1979

The remaining volumes will be published as a sequence of Volume Numbers of AGARDograph 300.

Volume Number	*Title*	*ation*
1.	Calibration of Air-Data Systems and Flow Direction Sensors by J.A.Lawford and K.R.Nippress	83
2.	Identification of Dynamic Systems by R.E.Maine and K.W.Iliff	1986
3.	Identification of Dynamic Systems Applications to Aircraft Part 1: The Output Error Approach by R.E.Maine and K.W.Iliff	1985
4.	Determination of Antenna Patterns and Radar Reflection Characteristics of Aircraft by H.Bothe and D.Macdonald	1986
5.	Store Separation Flight Testing by R.J.Arnold and C.S.Epstein	1986

At the time of publication of the present volume the following volumes were in preparation:

Identification of Dynamic Systems. Applications to Aircraft
Part 2: Nonlinear Model Analysis and Manoeuvre Design
by J.A.Mulder and J.H.Breeman

Flight Testing of Digital Navigation and Flight Control Systems
by F.J.Abbink and H.A.Timmers

Technqiues and Devices Applied in Developmental Airdrop Testing
by H.J.Hunter

Aircraft Noise Measurement and Analysis Techniques
by H.H.Heller

Air-to-Air Radar Flight Testing
by R.E.Scott

The Use of On-Board Computers in Flight Testing
by R.Langlade

Flight Testing under Extreme Environmental Conditions
by C.L.Hendrickson

Flight Testing of Terrain Following Systems
by C.Dallimore and M.K.Foster

Annex 2

AVAILABLE FLIGHT TEST HANDBOOKS

This annex is presented to make readers aware of handbooks that are available on a variety of flight test subjects not necessarily related to the contents of this volume.

Requests for A & AEE documents should be addressed to the Defence Research Information Centre, Glasgow (see back cover). Requests for US documents should be addressed to the Defense Technical Information Center, Cameron Station, Alexandria, VA 22314 (or in one case, the Library of Congress).

Number	*Author*	*Title*	*Date*
NATC-TM76-1SA	Simpson, W.R.	Development of a Time-Variant Figure-of-Merit for Use in Analysis of Air Combat Maneuvering Engagements	1976
NATC-TM76-3SA	Simpson, W.R.	The Development of Primary Equations for the Use of On-Board Accelerometers in Determining Aircraft Performance	1977
NATC-TM-77-1RW	Woomer, C. Carico, D.	A Program for Increased Flight Fidelity in Helicopter Simulation	1977
NATC-TM-77-2SA	Simpson, W.R. Oberle, R.A.	The Numerical Analysis of Air Combat Engagements Dominated by Maneuvering Performance	1977
NATC-TM-77-1SY	Gregoire, H.G.	Analysis of Flight Clothing Effects on Aircrew Station Geometry	1977
NATC-TM-78-2RW	Woomer, G.W. Williams, R.L.	Environmental Requirements for Simulated Helicopter/VTOL Operations from Small Ships and Carriers	1978
NATC-TM-78-1RW	Yeend, R. Carico, D.	A Program for Determining Flight Simulator Field-of-View Requirements	1978
NATC-TM-79-33SA	Chapin, P.W.	A Comprehensive Approach to In-Flight Thrust Determination	1980
NATC-TM-79-3SY	Schiflett, S.G. Loikith, G.J.	Voice Stress Analysis as a Measure of Operator Workload	1980
NWC-TM-3485	Rogers, R.M.	Six-Degree-of-Freedom Store Program	1978
WSAMC-AMCP 706-204	—	Engineering Design Handbook, Helicopter Performance Testing	1974
NASA-CR-3406	Bennett, R.L. and Pearsons, K.S.	Handbook on Aircraft Noise Metrics	1981
—	—	Pilot's Handbook for Critical and Exploratory Flight Testing. (Sponsored by AIAA & SETP — Library of Congress Card No. 76-189165)	1972
—	—	A & AEE Performance Division Handbook of Test Methods for Assessing the Flying Qualities and Performance of Military Aircraft. Vol.1 Airplanes	1979
A & AEE Note 2111	Appleford, J.K.	Performance Division: Clearance Philosophies for Fixed Wing Aircraft	1978

Number	Author	Title	Date
A & AEE Note 2113 (Issue 2)	Norris, E.J.	Test Methods and Flight Safety Procedures for Aircraft Trials Which May Lead to Departures from Controlled Flight	1980
AFFTC-TD-75-3	Mahlum, R.	Flight Measurements of Aircraft Antenna Patterns	1973
AFFTC-TIH-76-1	Reeser, K. Brinkley, C. and Plews, L.	Inertial Navigation Systems Testing Handbook	1976
AFFTC-TIH-79-1	—	USAF Test Pilot School (USAFTPS) Flight Test Handbook. Performance: Theory and Flight Techniques	1979
AFFTC-TIH-79-2	—	USAFTPS Flight Test Handbook. Flying Qualities: Theory (Vol.1) and Flight Test Techniques (Vol.2)	1979
AFFTC-TIM-81-1	Rawlings, K., III	A Method of Estimating Upwash Angle at Noseboom-Mounted Vanes	1981
AFFTC-TIH-81-1	Plews, L. and Mandt, G.	Aircraft Brake Systems Testing Handbook	1981
AFFTC-TIH-81-5	DeAnda, A.G.	AFFTC Standard Airspeed Calibration Procedures	1981
AFFTC-TIH-81-6	Lush, K.	Fuel Subsystems Flight Test Handbook	1981
AFEWC-DR 1-81	—	Radar Cross Section Handbook	1981
NATC-TM-71-ISA226	Hewett, M.D. Galloway, R.T.	On Improving the Flight Fidelity of Operational Flight/ Weapon System Trainers	1975
NATC-TM-TPS76-1	Bowes, W.C. Miller, R.V.	Inertially Derived Flying Qualities and Performance Parameters	1976
NASA Ref. Publ. 1008	Fisher, F.A. Plumer, J.A.	Lightning Protection of Aircraft	1977
NASA Ref. Publ. 1046	Gracey, W.	Measurement of Aircraft Speed and Altitude	1980
NASA Ref. Publ. 1075	Kalil, F.	Magnetic Tape Recording for the Eighties (Sponsored by: Tape Head Interface Committee)	1982

The following handbooks are written in French and are edited by the French Test Pilot School (EPNER Ecole du Personnel Navigant d'Essais et de Réception ISTRES — FRANCE), to which requests should be addressed.

Number EPNER Reference	Author	Title	Price (1983) French Francs	Notes
2	G.Leblanc	L'analyse dimensionnelle	20	Réédition 1977
7	EPNER	Manuel d'exploitation des enregistrements d'Essais en vol	60	6ème Edition 1970
8	M.Durand	La mécanique du vol de l'hélicoptère	155	1ère Edition 1981
12	C.Laburthe	Mécanique du vol de l'avion appliquée aux essais en vol	160	Réédition en cours
15	A.Hisler	La prise en main d'un avion nouveau	50	1ère Edition 1964
16	Candau	Programme d'essais pour l'évaluation d'un hélicoptère et d'un pilote automatique d'hélicoptère	20	2ème Edition 1970
22	Cattaneo	Cours de métrologie	45	Réédition 1982

Number EPNER Reference	*Author*	*Title*	*Price (1983) French Francs*	*Notes*
24	G.Fraysse F.Cousson	Pratique des essais en vol (en 3 Tomes)	T 1 = 160 T 2 = 160 T 3 = 120	1ère Edition 1973
25	EPNER	Pratique des essais en vol hélicoptère (en 2 Tomes)	T 1 = 150 T 2 = 150	Edition 1981
26	J.C.Wanner	Bang sonique	60	
31	Tarnowski	Inertie-verticale-sécurité	50	1ère Edition 1981
32	B.Pennacchioni	Aéroélasticité — le flottement des avions	40	1ère Edition 1980
33	C.Lelaic	Les vrilles et leurs essais	110	Edition 1981
37	S.Allenic	Electricité à bord des aéronefs	100	Edition 1978
53	J.C.Wanner	Le moteur d'avion (en 2 Tomes) T 1 Le réacteur .... T 2 Le turbopropulseur	 85 85	Réédition 1982
55	De Cennival	Installation des turbomoteurs sur hélicoptères	60	2ème Edition 1980
63	Gremont	Aperçu sur les pneumatiques et leurs propriétés	25	3ème Edition 1972
77	Gremont	L'atterrissage et le problème du freinage	40	2ème Edition 1978
82	Auffret	Manuel de médicine aéronautique	55	Edition 1979
85	Monnier	Conditions de calcul des structures d'avions	25	1ère Edition 1964
88	Richard	Technologie hélicoptère	95	Réédition 1971

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14. Abstract

This volume in the AGARD Flight Test Techniques Series treats stores separation testing from the overall systems standpoint. All aspects of testing are described from the time of identification of a particular aircraft/store requirement through all steps leading to the establishment of a satisfactory employment envelope. Considerable emphasis is placed on the planning and execution of the flight test phase of the stores clearance programme, including the definition of a basic structure, and a set of procedures which will maximise the safe and efficient execution of such a programme.

This AGARDograph has been sponsored by the Flight Mechanics Panel of AGARD.

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Advisory Group for Aerospace Research and Development, NATO
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